THE HARDNESS OF WOOD

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THE HARDNESS OF WOOD

p.35 Line 5 - for "decreases" read "increases"

p.92 Caption should read "for balsa, kahikatea, hard beech and Douglas fir"

p.129 5 lines from end - for "raltionship" read "relationship"

p.133 Line 5 - for "propogation" read "Propagation"

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PREFACE

The Hardness of Wood is arranged in sections designated A to E. Each contains material which is organised into associated groups, hopefully forming a background to work covered in later sections. Section A is primarily a review of literature, Section B considers a number of variables in hardness testing, such as loading rate, sample orientation and shape of tool, as well as introducing an investigation into foamed polyurethane indentation. Section C presents an investigation into the relationship between Wedge Hardness and other strength properties of wood, while Section D includes the application of wedges to cleavage testing and testing of board products.

Where possible, data and results are presented along with discussion and conclusions for each investigative unit. Where data was excessive, notably in Chapter 5, parts of the data have been removed to an appendix. Section E contains the Appendices, as well as the Summary, Acknowledgements and References.

ABSTRACT

This investigation covers the development of hardness testing in general, including reference to the considerable work done in this field with metals. Hardness testing of wood is reviewed from the early 19th century to its culmination in the development of a number of standard methods now in use for testing hardness. The effects of factors such as density, structure and environmental conditions are considered with reference to the literature.

Wood is tested on three faces using wedges and the Janka test tool to determine the influence of sample orientation on hardness results. The effect of loading rate is investigated and comment is made on loading rates and penetration depths used in the different methods.

Investigations into the hardness properties of rigid cellular polyurethane foams are also reported.

Evidence is submitted showing that woods should be considered as a range of materials - low density cellular and almost rigid-solid at the two extremes.

Correlations for Wedge Hardness with other strength properties and density of timber in the air dry state are given for New Zealand timbers and some overseas timbers covering a density range from 140 to 1270 kg/m^3. The Wedge test is shown to be capable of good prediction of many properties and is closely dependent on density. Correlations with green timbers were less good, but still show general agreement with trends in other strength properties.

Results indicate an application for the use of sharp wedges as an alternative method of determining cleavage

strength parallel to the grain.

Tests on particle board and fibreboard are not encouraging. A 136° wedge appears a useful guide to hardness on the board face, especially for use with thinner board, but does not reliably detect density gradient across the edge of the board.

Section A

INTRODUCTION

On considering the hardness of metals, O'Neill (1934) states: "like the storminess of the seas, it is easily appreciated but not so readily measured."

It is a concept which has long been applied, yet for wood has not been satisfactorily defined. There has been no lack of interest in the topic, indeed there have been many major studies throughout the world leading to at least seven different standard tests for static hardness measurement. In addition, there are several tests for measuring the dynamic hardness of wood, for example by measuring the height of rebound of a ball dropped onto the test surface.

Many of the methods in use have a number of shortcomings and this has led to the search for alternative techniques for hardness determination. Suggestions have been made that hardness test may indeed be totally invalid. Kollmann (1968) makes the following comment concerning the hardness testing of wood:

> "..... the variations of hardness for (such) a single arbitrary piece of wood are about of the same magnitude as for the whole species of wood concerned. This fact, the irregular course of the frequency curves, the correlation of hardness to crushing strength, and finally the variety of hardness tests not at all testing the resistance of the surface against penetration, should indicate the lack of validity of hardness tests. From this point of view, the similarity of the curves showing the dependence of hardness on the one hand, crushing strength on the other, on the moisture content of the wood, also supports the proposal to eliminate all hardness tests as they are now conceived."

Apart from the French Monnin test, all the tests presently standardised are based on indentation of a hemispherical tool into the surface of a sample. Many other shapes and sizes of tool have been investigated, particularly in Germany, but the predominance of the Brinell ball, as well as the version modified by Janka for use with wood and universally known as the Janka test, is evident from Table 1. It is significant to note that there is no German (D I N) standard which covers the testing of hardness in wood, especially considering the volume of work carried out in Central Europe.

Owing to the subjectivity of, or rather lack of, definition of the hardness of wood, the concept is not, in itself a particularly useful one. However, in that it is extremely easy to measure and the test is virtually non-destructive, it may well be valuable as a rapidly obtained guide to general strength properties of timbers. This would be particularly so if there was a reasonable correlation between hardness and other strength properties. This relationship could be a fairly loose one, for example if 60-70% of the relationship could be explained by a linear function. If the relationship were to be valid only for quadratic or high forms, then the value of the test would be lost as it would require additional computation to clarify the information recorded in the test. Since the indentation test is easier to perform than any other strength test, it would prove valuable if a good correlation would allow this simple procedure to be substituted for one of the more complicated timber strength tests. The excellent correlation between Janka hardness and compressive strength perpendicular to the grain has led to the Princes Risborough Laboratory (Building Research Establishment, U.K.) suggesting that the latter test need not be carried out at all and compressive strength be calculated from Janka hardness (Lavers, 1968).

It should be pointed out at this stage that, although considerable research has gone into an understanding of the structure of wood and its relationship to strength properties, it is only recently that attempts have been made to develop a theory of wood as a fibre-reinforced material and the subject has not reached the level of sophistication or advancement comparable to that of other materials. It is possible that, because wood has been in use for many centuries, less time has been devoted to study of the old, tried material while much effort has been afforded to studying and developing more 'modern' materials. In addition, lack of development may be partly due to the inherent difficulty in being unable to manufacture wood as a test material with clearly defined combinations of properties.

Key to Table 1

JIS - Japanese Standards Institute. JIS Z 2117 (1977)
ASTM - American Society for Testing Materials. ASTM D143-52 (1978)
BS - British Standards Institute. BS 373 (1957)
ISO - International Standards Organisation. ISO-3350 (1975)
AFNOR - L'Association Francaise de Normalisation
AFNOR B51-125 (1972) (Monnin): AFNOR B51-126 (1976) (Brinell)
DVM - Deutsche Industrie Norm. (DIN). DVM - Provisional C3011 (March 1934)

	JIS	ASTM	BS	ISO	AFNOR	AFNOR	DVM
Indenter	ball (Brinell)	ball (Janka)	ball (Janka)	ball (Janka)	ball (Brinell)	cylinder (Monnin)	ball (Brinell)
Indenter diameter	10mm	0.444in	11.28mm	11.28mm	10mm	30mm	10mm
Indentation depth	$1/\pi$mm	0.222in	5.64mm	5.64mm or 2.82mm	-	-	-
Indentation speed	0.5mm/min	0.25in/min	0.11mm/s	3-6mm/min	Max. load achieved in approx. 30s		-
Specified load	-	-	-	-	200 kgf for a 20mm wide sample		50kg (100kg for very hard woods)
Testface	T, R and End	T, R and End	T, R and End	T, R and End	T, R and End	R only	T, R and End
Hardness calculation based on	calotte surface	projected area	projected area	projected area	calotte surface	width of indentation	calotte surface

Table 1 - Methods suggested for the testing of hardness in wood.

1. THE DEVELOPMENT OF HARDNESS TESTING OF METALS

To understand the development of hardness tests on wood, it is necessary to outline the basis of hardness testing in general, particularly as a considerable amount of work on wood has been based on concepts which have proved suitable with metals. This has lead to the predominance of the ball as a testing tool for determining the hardness of wood.

The significance of the hardness of a material had been pointed out by Mohs in 1822 when he reported the scratch hardness scale for use in mineralogy. Even as early as 1860, Nordlinger had applied a similar scale to wood, but it was not until 1900 that a quantitative scale with sound scientific basis was described.

In the Brinell Test (Brinell, 1900), a spherical steel indenter 10mm in diameter is pressed into the sample under a fixed load, W. The Brinell Hardness number, H_B, is then calculated from the load and the curved area of the indentation. The chordal diameter, d, of the resulting impression is measured and the Brinell Hardness number obtained using the formula:

$$H_B = \frac{2W}{\pi D^2 \left[1-\sqrt{[1-(d/D)^2]}\right]}$$

where D is ball diameter

For geometrically similar indentations, H_B remains constant (Kick, 1885). For any other situation H_B depends on the load and the size of the ball (Tabor, 1951).

In the initial Brinell test, the curved surface area of the indent was used to try to compensate for the work hardening of the metal, so that the hardness was independent of the size of the indentation, at least to a first approximation. However, this approach does not give the mean pressure over the indentation area. Meyer (1908) showed that mean pressure between sample and indenter should be based on projected area of the indentation. The Meyer hardness, load divided by projected area, is a more satisfactory physical concept than Brinell Hardness in that it is essentially constant and independent of load.

Ludwik (1908) introduced a conical indenter as an alternative to the ball. He used a diamond indenter having an included angle of 90^o and determined hardness as mean pressure over the surface area of the impression. He showed that the hardness determined by this method was independent of load though dependent on the angle of the indenter. This would be expected, again using the argument of geometric similarity.

In 1922, Smith and Sandland developed a pyramidal diamond indenter which was to become widely accepted as the Vickers Hardness Test. The opposing faces of the pyramid made an angle of 136^o. This angle was decided upon by analogy with the Brinell test. It is the angle subtended by tangents to the ball at the points where the average chordal diameter of test impressions would lie.

For a ball of diameter D indentations range between 0.25D and 0.5D. The average is 0.375D, equivalent to 136^{o}.

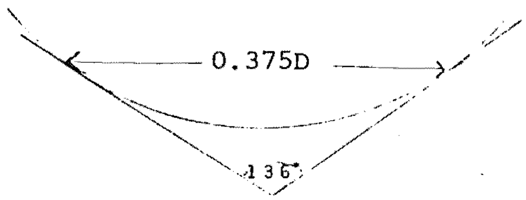


Fig. 1

The hardness is based on the surface area of the indentation derived from the mean value of the length of the diagonals of the indentation.

Another pyramidal tool in use is the Knoop indenter (Knoop, Peters, Emerson, 1939). This has included angles of 130^{o} and $172^{o}30'$ as indicated in diagram Fig. 2. The indentation is a parallelogram in which the long diagonal is approximately seven times the length of the short diagonal. Hardness is based on the projected area of the indent. After removal of the indenter the smaller diagonal may be considerably reduced by elastic recovery though the longer diagonal changes very little. The longer diagonal is used as a basis for determining hardness while the change in the shorter diagonal may give some indication of the elastic properties of the material. The depth of indentations with this indenter can be of a very low order enabling surface properties to be examined. Major applications for the Knoop indenter include investigation of surface properties and study of anisotropic materials.

The Rockwell Hardness Test is based on the measurement of the depth of penetration. A load of 10kg is applied to the surface of the material and depth of penetration is measured. This is used as a zero reference point. A further load of 90kg is applied and then removed, leaving the minor load, and the net change in penetration depth is recorded from a dial guage to give a hardness reading. For soft materials a spherical indenter is used (Rockwell 'B') and for harder materials a hemispherically tipped conical indenter (Rockwell 'C') .

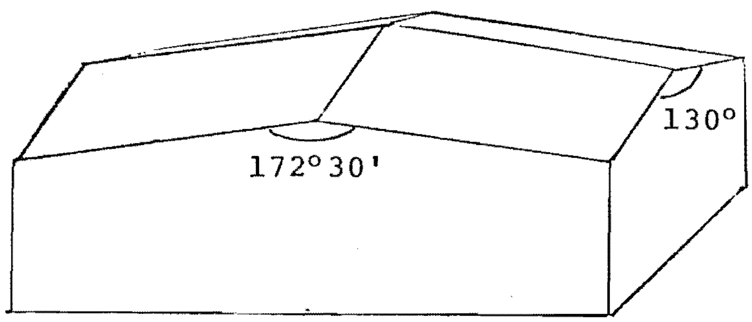


Fig. 2 - Knoop indenter - the length is seven times the breadth.

THE MEANING OF HARDNESS - IT'S APPLICATION TO METALS

It is evident that indentation hardness measurements on metals are essentially a measure of the yield stress or elastic limit of the material under test. The yield pressure between the metal and the indenter when plastic flow has occurred is about three times the effective yield stress of the metal (Tabor, 1951). On removal of the indenter, some elastic recovery occurs, but mainly in the depth of the indentation, projected area recovering only slightly. Calculated yield pressure will then depend on the criteria used for determination. Further complication may arise if there is appreciable "piling-up" or "sinking-in". In a perfect metal, i.e. highly work hardened, plastic deformation occurs close to the indenter and metal is displaced upwards, 'piling-up' around the indenter. For a metal in the annealed state, plastic deformation in the early stages produces work hardening of the material close to the indenter, so that a sort of 'cap' is formed which sinks with the indenter. Metal from further away from the indenter is then displaced preferentially and moves out at the surface a distance away from the indenter.

With indenters which give geometrically similar impressions, such as cones and pyramids, the mean pressure to give plastic flow is independent of the indentation size. Thus the hardness is conveniently the same at any value of load . It does mean, however, that the amount of work hardening of the metal cannot be calculated. In using spherical indenters, the shape of the impression changes with its size, so that as the indentation increases, the amount of work hardening, and hence the elastic limit, also increases. The use of spherical indenters means that the size of the load and the indenter have to be specified. The benefits, on the other hand, are manifest in the information provided on the degree of work hardening and stress-strain characteristics of the metal.

The background provided by hardness investigations on metals should be thoroughly understood before the methods are applied to wood. To dismiss all indenters other than the sphere because it has proved so useful with metals would be to ignore the convenience of valid methods, since the advantages of work-hardening information are of little value with wood.

2. INVESTIGATION OF HARDNESS PROPERTIES OF WOOD

2.1. DEVELOPMENT OF HARDNESS IDEAS IN EUROPE

The idea that different woods have widely differing properties has been held for as long as wood has been used. However, though these properties are easily appreciated measurement of them can prove to be difficult.

In 1860, Nordlinger made an attempt to quantify the 'Hardness' of wood. He decided that it would be impossible to determine an absolute value of hardness, and so based his categorisation on experience in the use of tools for woodworking. His hardness scale, in which he acknowledges the subjectivity of his system in the name "Guide to the hardness of timbers", grouped woods into eight hardness classes.

Forty years later, Dr Gabriel Janka published the first wood hardness report based on a scientific approach (Janka, 1906). For several years, Janka had worked on the problem of surface properties of wood, particularly in situations where the wood was exposed to surface wear. His first tests were carried out using a $10cm^2$ cube punch pressed into the endgrain of dressed spruce. He noted that the load required increased with density of the sample and also with the number of annual rings. Later this method was modified by reducing the probe size to $1cm^2$ and was used to test the hardness of timbers used for cobblestones (Janka, 1902).

In 1904 Busgen published the first comprehensive list of the hardness of timbers. His measuring technique was to embed a steel needle 2mm into a sample by adding weights to the needle. This was done using a modified Schermbeekshen soil testing machine, the weight in grams giving the hardness of the wood. Busgen suggested a modification of Nordlinger's table based on the load required to reach the 2mm for each species.

1.	soft:	1 - 10g	5.	40 - 50g	
2.		10 - 20g	6.	50 - 60g	
3.		20 - 30g	7.	70 + g	Very Hard
4.		30 - 40g			

The advantages of this method were politely dispelled by Janka in 1906 in his paper "Die Harte des Holzes". This comprehensive report, which presents the argument behind the widely used Janka Ball test, dismissed Busgens test as comparable with a nail being driven into wood. The wood is likely to split and the result is more likely to be an expression of inter-fibre adhesion than of hardness. In addition the small size of the probe leads to an enormous amount of variation so that the results are not a true reflection of hardness values.

Janka based his new test on the work published by Brinell in 1900. The main advantages that Janka saw in the Brinell test were the ability of the test to give consistent results and the use of the test on finished products without causing damage. However, Janka partly nullified this second advantage in his modification of the Brinell test by choosing too large an indentation depth. In his development of the test, Brinell had used the 10mm ball loaded to 50kg on all samples. He measured the width of the indent using a travelling microscope and from this worked out the hardness in kg/mm^2 based on the curved area of the indent. This method was, however, unsatisfactory for spongy or large pored woods because of the difficulty in measuring accurately the width of the indent. Janka's proposal was to overcome this problem by changing the principle. Instead of measuring the indent, Janka indented to a given depth and measured the load required to do this. He further refined the method to simplify operation by choosing a ball diameter of 11.28 mm and indenting to a depth of half the diameter. This gave a projected area of the indentation of exactly $1cm^2$, so that the hardness would be given directly by the load recorded. Other refinements included a collar around the tool at the diameter of the ball and a sleeve on the collar to aid levelling of the sample.

Janka was aware that the shape of the indenting tool might have some effect on hardness. He argued that the ball was unrelated to any woodworking tools and the fibres would not be cut, split or ripped. His reasoning here is unclear as splitting and ripping do occur in practice. In addition, Janka said that the shape of the ball meant that, as indentation progresses, new, undisturbed wood is compressed at the edges of the indent to the advantage of the test. Although this would be an advantage over the flat punch or the needle, Janka does not apply this reasoning to his wedge or cone tools even though they progress in a similar way as depth of indentation increases.

This predisposition toward the ball shaped tool did not deter Janka from investigating tools of other shapes. In order to find out how suitable they were for hardness testing he investigated the cone ($1cm^2$ base and 1cm in height), the wedge (1cm square base and 1cm in height) and a 1cm^2 punch type probe. His conclusions are of considerable interest.

With the ball, resistance of sample, when indentation is greater than a quarter of the radius, begins to reduce with increase in depth, more so with less dense timbers. With the cone probe, the effect is the opposite, resistance increasing as depth of indentation increases. With the wedge the resistance is proportional to indentation depth.

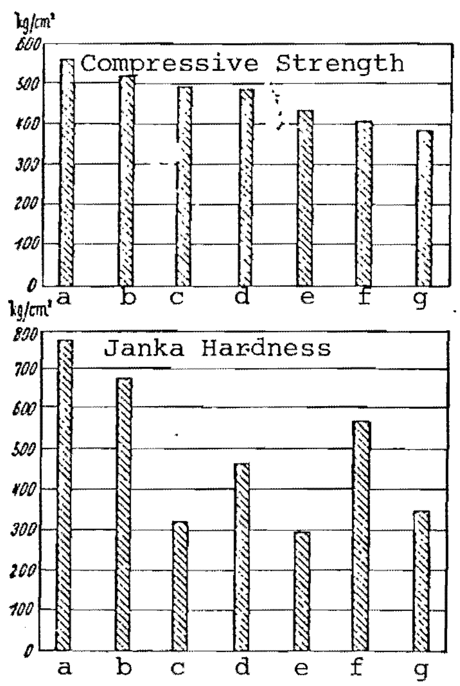
Janka's arguments against these tests are reasonable although some of the tests are badly conceived and a number of problems could have been avoided by minor alteration. He criticises the cone because of its tendency to cut the fibre bundles and push them sideways and because of its excessive penetration. The resistance to penetration of the cone does not reach that associated with the ball and Janka suggests this could be because the cone is able to push the harder growth bands to one side. This may be partially true, but it is more likely that failure of fibres under his very sharp cone is responsible for this effect. No cutting type failure occurs in the ball test initially. The cutting and shearing argument is also levelled against the wedge especially as the wedge is narrower than the test sample, causing interference from edge shear. The square punch probe shows a totally different effect and maximum pressure is reached very early in the test.

It seems likely that, in trying to parallel these tests for comparison, Janka used non-spherical tools which simply did not measure hardness: cones and wedges with much blunter angles might possibly have given him better results, and the use of a wedge tool wider than the sample would have avoided edge shear effects. These possibilities are discussed more fully in a later section.

After the publication of Janka's work, hardness became the topic of numerous investigations. Virtually all of these were based on either the Janka or Brinell principle and many made attempts to overcome some of the shortcomings thrown up in the discussions. Stamer (1929) pointed out that for softwoods the Janka hardness (load/projected area) decreased with penetration depth. However, for hardwoods there was little change in hardness as the tool progressed into the wood. Thus, he suggested, one could expect that, for a softwood of reasonable strength characteristics, the Janka hardness would be anomalously low. Results published by Hoeffgen in 1938 supported this idea. Hoeffgen had departed from the ball principle and had used a flat rectangular punch 5 x 20mm to measure hardness. Not surprisingly, his punch hardness results correlated extremely well with compressive strength. The test is a simple compression test with added shear effects at the indenter edges. His results do show, however, that the softwoods have very low Janka hardness when compared with hardwoods and in the light of their compressive strength values (See Fig. 3).

The irregular relationship between hardness and penetration depth led Morath (1932) to apply the Brinell test for metals to wood. The advantage of the Brinell test was that the depth of penetration was slight for medium density woods avoiding the main drawback of Janka's method. However, it was necessary to specify three separate standard loads of 50kg, 10kg and 100kg respectively for medium, low and high density woods. This did not give a sound basis for the comparison of hardness values.

Pallay (1937/8), unsatisfied with several aspects of both Janka and Brinell methods, describes a method proposed by Krippel. (Pallay 1937, 38, 39). In order to improve reliability of results and make the test easy to perform, a much larger hemisphere would be used. Huber (1938) had also proposed this and suggested that the Brinell test should be modified by using a 30mm diameter ball. This would allow a much shallower indentation to be made while maintaining a large contact area to give a good hardness average. Pallay, however, criticised the Brinell method in that it was difficult to measure an imprint in wood with any accuracy (especially if the imprint was an ellipse brought about by the anisotropy of wood). Krippel's method describes a hemisphere of 31.831mm embedded to 2.5mm. This gives an impression of diameter 25.466mm and area $2cm^2$. Thus half the maximum load gives the hardness directly. This method did not gain acceptance even though it had the benefits of both the Janka and Brinell without the serious shortcomings of either.



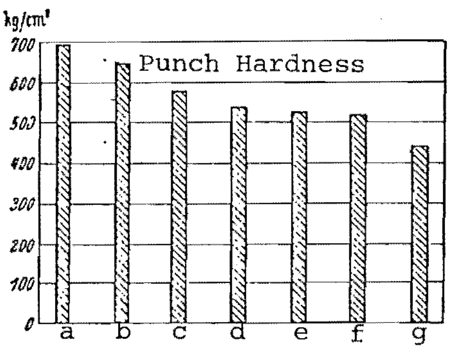


Fig. 3 - Results after Hoeffgen (1938)

(a) and (b) Beech
(c) Spruce
(d) Alder
(e) Pine
(f) Poplar

2.2. ORIGIN OF THE FRENCH STANDARD TEST FOR STATIC HARDNESS: THE MONNIN TEST

Janka's modification of the Brinell test was readily accepted around the world. The United States, Canada and the United Kingdom have adopted and retained the method as a standard. In Germany a Provisional Test (DIN DVM C3011) was based on the Brinell test, but has never been accepted as a standard.

Typically, the French were to provide a major departure from the ball type test in the form of the "Chalais" hardness test (Monnin, 1919). The Janka method is criticised because of the deformation caused when the indenter is embedded beyond a certain, relatively small limit. Tearing, shearing and crushing are characteristic of the test making it very difficult to know exactly what property is being tested. To avoid these problems a new test was proposed based on a steel cylinder rather than a steel ball.

With the cylinder, it had been determined that the depth of penetration remained proportional to load for loads up to about 150kg and much higher for harder woods. The indentation tool used was a cylinder of 15mm radius, chosen because it was considered to be a neutral penetrating body, an idea discussed earlier by Janka. The only justification for choosing this size of tool appears to be that it was available as part of the standard equipment for static bending tests. However, the Hardness number as calculated in this method is dependent only on the load/penetration depth relationship, the diameter of the tool is not included in the formula, unlike the Brinell formula. This is not entirely correct since a cylinder of a different diameter will give a different penetration depth at a fixed load.

For a load P, a depth of penetration, t, will result and because of the approximately straight line relationshp between the two, it is possible to state the Hardness number, M, in the following manner:

$$M = \frac{P}{l\ t \times 100}$$ (where l is the width of the sample).

With some refinement, this method known as the Monnin Test is in use as a standard in France (AFNOR NF B51-125 January 1972). The Monnin Hardness number is stated as $^{1}/t$, t being obtained from a table relating the width of the impression to the depth of the indentation. The width of the impression is relatively easy to measure, though not accurately (Sunley, 1965).

The advantages of this test over the Janka test are numerous. Apart from the abovementioned 'neutrality' of the tool, the test does not require large depths of penetration. Additionally, the tool used allows a much greater area of wood to be tested, thus taking into account the variability of wood between, for example, growth rings. It is interesting to note, however, that the test is only carried out on the radial face. The argument here is that on the tangential face the hardness can vary with penetration depth and hence the result is not valid. The hardness test on the endgrain is simply a localised, non-uniform, axial compression test.

More work on the cylinder type of test was undertaken in 1943 by the French National Wood Testing Institute. (Campredon and Gauthier, 1943 - 44). The size of the indenter was considered, both in terms of the diameter and the width of the cylinder. By increasing the cylinder width, more wood is included and some variability may be removed. It was also found that the ease of measurement of the imprint was improved as the cylinder diameter decreased, mainly by overcoming the effects of surface roughness. The smaller cylinders also gave a better separation of hardness values, particularly at lower loads.

Although this work led to the choice of a 25mm wide cylinder of 10mm diameter, the test tool described by Monnin has remained the Standard.

In order to place wood in the general pattern of hardness testing, AFNOR also standardises the Brinell test method for wood (NF B51-126, 1976).

2.3. WOOD HARDNESS TESTING IN JAPAN

Hardness testing of wood in Japan has led to yet another standard specification which is unlike it's ASTM or AFNOR counterparts.

Much of the Japanese work was influenced by German research, resulting in a confused period marked by alternation in preference for the Janka or Brinell method.

Moroto (1909) published the first hardness test in Japan based on the Brinell method, using a 30mm ball. Mori (1922) reported a Janka type test and Tanaka (1923) used the exact Janka method in his work. However, in 1925 Tanaka published results based on the Brinell test. The Janka method was again favoured in 1933 (anon., from Miyajima, 1965) but by 1937 the Brinell method was again being used. A provisional standard based on the Brinell method was published in 1939.

The first full standard for hardness testing of wood was JIS A 1011 (1954). This test is a type of Janka method and it is worthwhile noting some of the points made in the explanation of the method given by Sawada (1956). Problems encountered in the Brinell test are pointed out and the solutions to these drawbacks are outlined as follows.

A relatively long time is required in measuring an indentation width after loading, making the Brinell test unnecessarily long. In this type of measurement, operator error could be highly significant as the indentation boundary was not always clear. In addition, the elastic recovery of the material varies with moisture content. This leads to the unacceptable situation where a green timber, because of its increased elastic recovery, is harder than the same timber in the dry state.

The new method (JIS A 1011) required that a 10mm diameter ball be indented to a given depth, in this case $^1/\pi$mm($\simeq$0.32mm), and the load required be read. This gives a negligible amount of surface damage along with satisfactory results. In order to calculate hardness, however, the reading in kg/10 actually gives a Brinell type result. The formula used to calculate hardness is:

$$H = \frac{P}{\pi Dh}$$ where P is load

in kg, D is diameter of Ball = 10mm and h is depth of indentation = $^1/\pi$mm. This is an accurate approximation for the Brinell hardness formula and indicates the ratio of load to the area of the curved surface. It does not, however, give the mean pressure over the surface of the indentation (Tabor, 1951).

Although it is accepted that Brinell hardness is only comparable for indentations of geometric similarity (Tabor, 1951), Miyajima (1955) found that for small indentations in *Quercus crispula* there was a linear relationship between load and indentation depth for the 10mm ball. Ohsako and Yamada (1965) found that this relationship held loosely for loads up to 50kg, though it seems that Brinell Hardness does in fact increase with penetration depth.

Miyajima (1961), in a comparison between ball and cylinder methods, is strongly in favour of the ball method. He criticizes the cylinder (Monnin) method after results indicated that test carried out using different loads (as suggested in the AFNOR specification) gave different hardness numbers for the same timbers. He also points out the problem of intrusion of the edge of the contact region below the surface plane of the sample. This type of exaggerated sinking in, caused by lifting of the free ends of the sample, means that hardness measured by penetration of the tool bears no resemblance to the result taken from the impression width.

In a more comprehensive study on indentation hardness of wood, Miyajima (1963) considers in detail the different methods of testing which had been suggested over the preceeding sixty years. He finds some form of inconvenience or inconsistency in every method, but concludes that the ball method has most merit. He suggests that to improve results on wide grain woods, it would be preferable to use a 30mm diameter ball rather than one of 10mm diameter. For convenience the ball is indented (at a rate of 0.5mm/mm) to a depth of $5/3\pi$ mm so that the hardness is then 1/50 of the load reading.

DEVELOPMENT OF ALTERNATIVE HARDNESS TEST METHODS

Two main areas of departure from existing test methods have been considered. It is possible to devise an entirely different test, for example based on indenters of different geometry such as cones or pyramids. Alternatively existing methods may be interpreted or analysed differently with rewarding results. Both of these possibilities have been considered.

Kumichel and Holz (1955) reported a method based on the use of the Höppler "Konsistometer". (Höppler, 1940). This machine was designed for several applications, it's major uses being in the measurement of the rheological properties of different materials, measurement of viscosity and plasticity, the study of elastomeric materials and for the measurement of Hardness. A dissatisfaction with existing hardness testing methods had led Kumichel and Holz to investigate the possibility of using a cone shaped indenter for hardness testing. The standard cone probe of the Höppler machine was considered suitable, having an angle of $53^{\circ}08'$. This meant that the height of the cone was equal to the diameter of the projected impression area, allowing Höppler's "cone flow point", F_k, to be calculated (Höppler, 1940) as

$$F_k = \frac{4G}{T^2\pi} \qquad \text{where } G = \text{load}, \quad T = \text{indentation depth}$$

Kumichel and Holz suggest that only the plastic portion of the deformation should be measured and so time should be allowed after indentation for elastic recovery to take place before indentation depth is measured. It is unlikely, however, that the depth recovery will be the same as the width recovery. In this case it is possible that the projected area computed bears no resemblance to the real projected area either during or after indentation. The results of tests using the cone show that F_k is independent of indentation depth although the variation from the mean of F_k was not the same for different values of depth. Further work by Nedbal (1957) indicates the suitability of the cone for determining hardness especially as it appears to be capable of finer distinctions than is the Brinell ball test. It is interesting to note that Nedbal and Kumichel *et al* found that radial and tangential hardness was higher than endgrain hardness when testing with the cone. However, when using the Brinell tool, endgrain hardness was higher. This shows that the two methods do indeed measure different qualities.

Weatherwax, Erickson and Stamm (1948) described a method to determine the hardness of wood based on the use of a standard size Janka tool. In the search for a test suitable for very dense materials such as compressed wood products, staypak and compreg, as well as light woods such as balsa, a Janka ball was pressed into samples at a rate of 0.508mm/min. Penetration was recorded to an accuracy of 0.025mm. It was found that for the major part of the test range the relationship between load and penetration depth was linear. Deviation from linearity increases as penetration depth rises above 2mm (less than half the full Janka indentation depth). It is likely, though, that it is not in fact linear at any time. After initial contact there would be a very rapid rise in contact area for a small indentation. This necessitates a rapid increase in load even though indentation depth is slight. The rate of increase of contact area then slows down, eventually becoming very slight for even large penetration increases. This accounts for the fall off of load increase as penetration proceeds. It is likely that a sort of "work hardening" occurs as the indentation increases. This may be due to formation of a cap of crushed material underneath the indenter, but will in any case complicate the curve. However, it is evident from results in any Janka test that the early portion of the load/penetration curve can be interpreted as approximately linear soon after initial contact.

Weatherwax *et al* went on to use this linearity by expressing hardness in terms of the slope of the straight line, which they designated hardness modulus. A relationship was determined relating hardness modulus H_M to density, ρ. This relationship

$$H_M = \alpha\rho^{\beta}$$

is of the same form as the Janka hardness/density relationship.

Further work using this method (Lewis, 1968) indicates that the method correlates well with Janka hardness, and low indentations in the order of 2.5 mm are required to determine the slope of the line. This is particularly useful in testing composite wood products, where delamination caused by excessive penetration can be a problem.

3. FACTORS AFFECTING THE HARDNESS OF WOOD

3.1. DENSITY AND STRUCTURE

Of the parameters which may affect the hardness of wood, density is undoubtedly extremely influential. Indeed, the relationship between hardness and density has been analysed and documented by many workers over the last 80 years. Janka (1906), working with several species, stated that the hardness of wood was approximately proportional to density. He did, however, point out that there were some serious deviations from the general rule, especially where attempts were made to compare species having widely different anatomical structure. In such cases the anatomy of the woods may have an effect which will be superimposed on the effect of changing density. Janka notes that for wood at constant temperature and moisture content, variations in density and anatomical structure together account for virtually all the detectable changes in hardness. For example, with samples of *Picea abies*, as density rises from around 0.3 g/cc to 0.52 g/cm^3, the side hardness increases gradually from 118.5 kg/cm^2 to 260 kg/cm^2. On the other hand samples of Olive show a hardness of 665 kg/cm^2, while Oak samples have much higher hardness at 960 kg/cm^2. Both woods have a density of 0.75 g/cm^2, but differ structurally. It may be seen from Table 3 that the density is less variable than hardness, suggesting that some of the variability in hardness is derived from a source other than density.

Trendelenburg (1933) developed relationships between Brinell hardness, H_B, and density, ρ, for American and

European woods. They were of the form:

$$H_B = \alpha\rho^{\beta}$$

For European woods on endgrain

$$H_B = 1180\rho^{1.62} \quad (kg/cm^2)$$

For American woods on endgrain

$$H_B = 1200\rho^{1.53} \quad (kg/cm^2)$$

For European woods, side hardness

$$H_B = 670\rho^{2.14} \quad (kg/cm^2)$$

For American woods, side hardness

$$H_B = 680\rho^{2.00} \quad (kg/cm^2)$$

Ylinen (1943) looked at a range of commercial timbers and suggested that, even accepting the validity of Trendelenburg's findings, it would be equally appropriate to describe the relationship between hardness and density by fitting an equation of the form:

$$H_B = \alpha + \beta\rho$$

For American timbers in the airdry state, he found the following held well for end hardness and side hardness:

End hardness: $H_B = -213.3 + 1263.3\rho \quad (kg/cm^2)$

Side hardness: $H_B = -145.4 + 664.2\rho \quad (kg/cm^2)$

The diagram shows the degree of prediction which can be expected from these relationships. (Fig. 4).

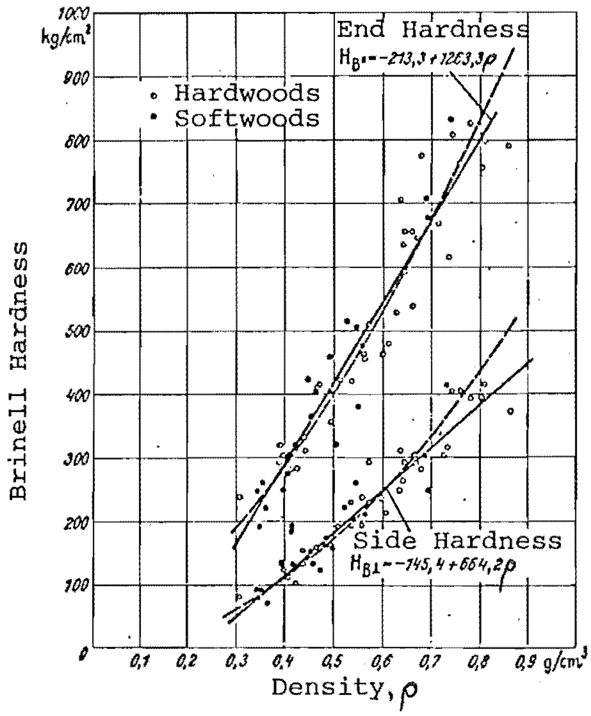


Fig. 4 - Brinell Hardness versus Density for American woods. 15% Moisture content (After Ylinen, 1943).

Further work by Miyajima (1955, 1963) and Sawada, Tsujik and Kondo (1955) indicates that a relationship of the linear form, as suggested by Ylinen, is reasonably valid. Miyajima states that hardness, as measured by the Brinell method, increases directly with increase in density. However, there is general agreement that for woods of a given density large variations in hardness will occur due to differences in anatomical structure. In particular, the orientation of the sample will have a considerable effect on hardness since wood is an anisotropic material.

Sawada *et al* noted that, for samples of Sugi and Japanese spruce, hardness on the end grain was generally higher than side hardness and latewood had greater hardness than early wood. The ratio of hardness values for end hardness, H_l, radial hardness, H_r, and tangential hardness, H_t, was found to be:

$$H_l:H_t:H_r = 1:0.30:0.34$$

and for earlywood, H_e, and latewood, H_s,

$$\frac{H_{le}}{H_{ls}} = 0.62 \qquad \frac{H_{te}}{H_{ts}} = 0.52 \qquad \frac{H_{re}}{H_{rs}} = 0.60$$

Miyajima concludes that the side hardness is about 25-40% of end hardness, tangential hardness was slightly higher than radial hardness (125-135%) in most hardwoods except *Ulmus* species in which there was no difference.

With regard to growth rates, Miyajima states the following. For diffuse-porous woods such as *Cercidiphylum, Sorbus* and *Acer* species, rate of growth has apparently little effect on hardness. For ring-porous species such as *Ulmus* and *Quercus* hardness increases with increasing annual ring width, especially for the range 0.5 - 2.00mm. For semi-ring-porous species such as *Prunus* hardness increases with ring width from 2 - 5mm. For softwoods such as *Abies, Larix* and *Pinus* species, and optimum growth rate for high hardness values occurs at a ring width of 1 - 2mm.

Janka (1906) also considered the effect of ring width and decided that there was no definite relationship with hardness. He found that the percentage of latewood present had much more influence and hardness tended to increase with an increasing latewood percentage. Miyajima (1955) noted that the Brinell hardness increased for increasing ring width of *Quercus crispula* , to a maximum value at a ring width of around 2.2mm. Hardness reduced for ring widths above this; but Miyajima notes that these very wide rings were in samples obtained from near the pith. The loss in hardness is possibly due to the presence of juvenile wood, but Miyajima does not comment on this.

Indeed, any analysis of variations of hardness with growth rate must consider the effects of both structural change and variations in local wood density. The argument here is analogous with the present controversy surrounding the Japanese Building Authorities exclusion of radiata pine for structural uses due to its fast growth and consequently wide rings widths. The Japanese appear to deliberately confound the effect of fast growth rate with the wide annual rings found in juvenile wood of most species.

3.2. MOISTURE CONTENT AND TEMPERATURE

Although density and structure determine to a large extent the hardness of wood, no less important is the effect of the moisture content. On drying a sample of wood, free water in the cell cavities is removed first with no change in the strength properties. When the fibre saturation point is reached, that is when no free water remains, but the cell wall fibres remain fully saturated, an improvement in strength properties begins to occur. Some properties are considerably more sensitive to moisture content changes than others. Table 2 shows to what extent moisture affects the strength of wood.

Property:	Change per 1% change in M.C. below F.S.P. (%)
Static bending:	
Modulus of rupture	4
Modulus of elasticity	2
Work to proportional limit	8
Fibre stress at proportional limit	5
Compression parallel to grain:	
Fibre stress at proportional limit	5
Maximum crushing strength	6
Compression perpendicular to grain	
Fibre stress at proportional limit	5.5
Maximum shear strength parallel to grain	3
Maximum Tensile strength perpendicular to grain	1.5
Hardness:	
End	4
Side	2.5

Table 2 - Effect on strength properties of changing moisture content (data from USDA Wood Handbook 1955, revised 1974).

It is interesting to note that end hardness is much more sensitive to moisture changes than is side hardness, though compressive strength in the two directions both show sensitivities of approximately 5% strength loss per 1% increase in moisture content.

Kollman (1968) explains the reduction in strength with increasing moisture content by suggesting that water molecules between the microfibrils increase the separation and reduce intermicrofibrillar forces and therefore cohesion. This is indicated by the swelling of wood on sorption of water.

Janka (1906) observed the effect of moisture content on hardness for hardwoods and softwoods. In samples tested oven dry, at 10-12% moisture content, at 15% moisture content, and in the green state, the effect on hardness was similar to the reductions observed in other strength tests. Thus, hardness was about halved in going from the air dry (15%) state to fibre saturation point. The loss was about 50% in softwoods and about 35% in hardwoods. When the moisture content is reduced from air-dry to oven dry, properties such as compressive strength are improved considerably. However, Janka found that hardness did not increase by nearly as much as did compressive strength and for some species (*Picea, Abies* and *Quercus)* it actually reduced. In this case, total loss of water effects the bonding of the fibres and the samples become extremely brittle, splitting easily under test. This reduction in hardness was not reported by Miyajima (1955) in Brinell hardness tests on *Quercus cripula* where the hardness increased as moisture content decreased and oven-dry wood was considerably harder than air-dry samples. However, the maximum indentation depth achieved in these tests was approximately 1mm. In contrast, Janka indented to over 5mm resulting in complex deformation and tearing of the fibres and eventual splitting of the samples. This accounts for the decrease in hardness reported by Janka. Miyajima concludes that the ratio of hardness for green, air-dry and oven-dry wood is about 0.5:1:2 on each surface. The low penetration Brinell test used here is much more reliable than the Janka test, especially for denser timbers.

Kumichel and Holz (1955) found that hardness based on the projected area of a cone indentation decreased rapidly as moisture content increased, until the fibre saturation point was reached. It is to be expected that hardness determined by indentation will vary in the same way regardless of the shape of indenting tool, as all strength properties decrease with increasing moisture content until fibre saturation is attained (with the exception of shock resistance which increases with the enhanced pliability of wet wood).

The effect of temperature change on wood is somewhat dependent on moisture content. As moisture content increases up to fibre saturation point, the effect of temperature becomes more pronounced. In general the strength properties of wood decrease on heating and recover on cooling, the effect being immediate. However, if a high temperature is sustained for prolonged periods the strength properties may be irreversibly decreased.

Goring (1963) has shown that thermal softening points could be detected by heating powdered samples of lignin, cellulose and hemicellulose at a uniform rate. The powder was compressed under a constant load in a glass capillary and the softening point was regarded as being the temperature at which the powder collapses into a solid plug. The softening temperature of hemicellulose and lignin was significantly decreased by sorption of water and the transition point became more abrupt. Hemicellulose with sorpted water will begin to soften at about 50°C, lignin at about 90°C. In the dry state, softening points are around $130^{o} - 190^{o}C$.

For dry cellulose, no thermal softening is apparent until close to the melting point at around $360^{o}C$. In addition water has no effect as it is not able to penetrate the crystalline core of the cellulose microfibrils where all the hydroxyl groups in the glucose residues - on the C_2, C_3 and C_5 carbon atoms - are able to form strong hydrogen bonds with their close packed neighbouring cellulose chains. X-ray diffraction studies show that the size of the cellulose unit cell is unaffected by moisture, indicating that water doesn't penetrate the unit cell. Because of the conformation of the cellulose unit, it is very easy for cellulose chains to pack together leading to a very strong inter-chain bonding. Each molecule of cellulose is flat and ribbon-like with OH groups positioned so that they are available to form hydrogen bonds with adjacent groups, but without significant bond distortion or Van der Waals repulsion. In contrast, the other sugar residues - the components of the hemicelluloses - are rarely able to form long chain molecules that pack closely together in an ordered crystalline array. The hydroxyl groups of these sugars do not all lie in the same plane as the atoms of the ring structure. If the hydroxyl groups are present in any other orientation than that found in the sugar monomer of cellulose, β - D - glucose, (see Kollmann and Cote, 1968, p. 59) then they must lie axially, essentially perpendicular to the carbon ring structure, and so cause physical resistance when trying to bring the chains close together (Rees, 1967). Thus, water is unable to penetrate the highly ordered crystalline cellulose, but is able to penetrate the laterally disordered chains in amorphous regions of the cell wall and the paracrystalline cortex of the microfibril.

Here, other sugars, such as galactose and mannose, may be incorporated with the β - D - glucose residues. The paracrystalline cortex surrounding the crystalline core of the microfibril is thought to have all the chains running parallel to one another, but with lateral disorder, as the hydroxyl groups no longer lie neatly in the plane of the hexose carbon ring. Hence the effects of moisture and temperature on the properties of wood is due to their effects on the non-crystalline matrix of wood, while the crystalline cellulose is unaffected.

Kollmann (1940) found that the crushing strength, σ, of wood decreased with increasing temperature according to a straight line relationship and the slope of the line varies directly with density, ρ. At any temperature $T^{\circ}C$

$$\sigma_T = \sigma_o - 4.76\rho_o.T \qquad k\rho/cm^2$$

Sulzberger (1948) considered the effect of Temperature, density and moisture content on crushing strength and deduced that σ was most sensitive to temperature changes at a moisture content of about 11%. The mechanism involved here may be due to the sensitivity of wood components to the addition of water as discussed by Goring (1963) and mentioned earlier.

The strength of wet beech below freezing point was documented by Kollmann. It appears that the trend for frozen wood follows that for unfrozen wood as moisture content changes, but absolute values of strength are lower for the unfrozen state. However, as the moisture content approaches the point where a complete lattice of ice crystals is formed to stretch between the loading plates (about 85% moisture content for beech), the measured crushing strength for the frozen wood increases. Until the pressure is sufficient to cause the ice to melt, the ice structure carries the load and the wood shares only a small proportion of the load.

In bending, the strength and stiffness of wood decrease as temperature increases and the elastic modulus increases similarly (Thunell, 1942). Sulzberger (1948) found that in bending the deflection at fracture showed no great change with temperature below 12% moisture content, while at higher moisture content, deflection increases considerably with temperature, indicating a gradual softening process.

Ohsako and Yamada (1965), studying the indentation of wet *Chamaecyparis obtusa* and wet *Fagus crenata* with a steel ball 10mm in diameter, noted that Brinell hardness, H_B, could be related to temperature, T, by the following equation:

$$H_B = a + kT$$ where a is

the Brinell hardness of the sample at 0^oC, k is a characteristic coefficient of the specimen. For *C. obtusa* k = -0.6 and for *F. crenata* k = -1.0.

It is also likely that increased rates of creep are induced by movement of water, by continuous adsorption and desorption of water molecules through the wood, thus allowing rapid changes of hydrogen bonds between the polymer chains and water molecules. Relative humidity changes only slightly affect the rate of exchange, but the process is temperature dependent. (Gibson, 1965).

3.3. VARIABILITY OF STRENGTH PROPERTIES

Every material in use is subject to some variability in properties, but the degree of variability differs markedly with the material type. Wood, being a natural material, is affected by a number of changeable factors such as climate and the general environmental conditions under which the tree grows. Soil conditions and growing space, for example, will affect the tree growth so that even relatively clear wood may show a high degree of variability. The designer or engineer must be aware of the amount of variation encountered in wood if the use of wood in a load bearing situation is to be considered. The following table gives an indication of the degree of variation that can be expected in certain wood properties. Column (a) shows the coefficient of variation for timbers commonly used in the United States and column (b) refers to New Zealand indigenous species. The figures for the New Zealand species are considerably lower, probably because of the restricted sampling locality. No clear rule applies here, however, as variation within silver beech samples seems to be associated with locality, whereas variation in rimu samples is high even among samples from the same geographical locality.

Property	Coefficient of variation (%) (a)	(b)
Density	10	8
Static bending:		
Fibre stress at proportional limit	22	16
Modulus of rupture	16	12
Modulus of elasticity	22	16
Work to proportional limit	38	23
Compression parallel to grain:		
Fibre stress at proportional limit	24	18
Maximum crushing strength	18	13
Compression perpendicular tc grain:		
Fibre stress at proportional limit	28	21
Maximum shear strength parallel to grain	14	
Maximum tensile strength perpendicular to grain	25	
Hardness:		
End	17	13
Side	20	15

Table 3 - Variability of Strength Properties of wood.

(values based on results of approximately 50 species of wood; data from USDA Wood Handbook, 1955. New Zealand data from Entrican, Ward and Reid, 1951).

Site factors are obviously important in the latter case.

It may be of interest to compare the variability of some structural materials. As would be expected, materials which are subject to control during the manufacturing process are likely to be less variable than a natural material such as wood. It should be borne in mind also that the figures below are for clear specimens of wood and the variability of graded

Material		Average	Deviation	Coefficient of variability
Unseasoned wood	Bending Strength	51 N/mm^2	8 N/mm^2	16%
Concrete	Compression Strength	31 N/mm^2	4 N/mm^2	12%
Structural Steel	Tensile Strength	275 N/mm^2	25 N/mm^2	9%

(From Hoyle, J.R., Wood Technology in the Design of Structures (1972)).

sawn timber with its normal share of defects - knots, checks, slope of grain for example - is much larger again. This variability makes the engineers task of efficient design controls difficult and developments such as machine stress grading are of considerable importance in maintaining and developing a role for timber in engineering structures.

3.4. THE BEHAVIOUR OF CELLULAR MATERIALS

Wood is a highly complex cellular material. The rheological behaviour and mechanical properties are well documented (Kollmann and Cote, 1968, Koch, 1972). However, some of the work which has been done on simple cellular materials such as foamed plastics, glass and metals, may be applicable to wood.

Shaw and Sata (1966) studied the plastic behaviour of cellular materials using foamed polystyrene. The Brinell hardness test was carried out on samples of mild steel and on samples of foamed polystyrene. It was found that deformation underneath the indenter was much more localised for the foam than for the solid metal. It has been stated (Tabor, 1951, P. 50) that the ratio of Meyer hardness (load/projected area) and the flow stress in compression is approximately 3 for a solid material. The explanation here is that the surrounding solid materials acts as a restraint factor on the material undergoing plastic deformation. In the case of a cellular material of the type used by Shaw and Sata this ratio was found to be approximately 1. This would be expected of any material having a very low value of Poisson's ratio (foamed polystyrene $\simeq$ 0.03, solid metal $\simeq$ 0.5) since the restraining factor is negligible. It is likely that wood falls somewhere between the two extremes, this being affected by structure, density and species.

Wilsea *et al* (1975) carried the work on foam indentation further. Using an analysis based on the work of Timoshenko and Goodier (1934) they show that the Meyer Hardness of a low density cellular material would theoretically be approximately equal to its yield stress in compression. Experimental results indicate that this is true initially, but hardness tends to increase with increasing indentation depth. This may be due to the cap of plastically deformed material which is produced immediately below the indenter. The results should be applicable not only to foam, but to low density woods such as balsa. The work of Wilsea *et al* will be further considered in a later section.

3.5. THE RELATIONSHIP BETWEEN FLOW STRESS AND HARDNESS

Shaw and Sata (1966) working with foams found that the yield stress of a material, σ_y, was almost equal to the hardness H, of the material. They had used the Brinell test method to determine hardness. The analysis of the process of yielding caused by a multi-axial stress has been reported by Wilsea *et al* (1975). The stress system beneath a cylindrical indenter with uniform indentation pressure is shown in Fig. 5.

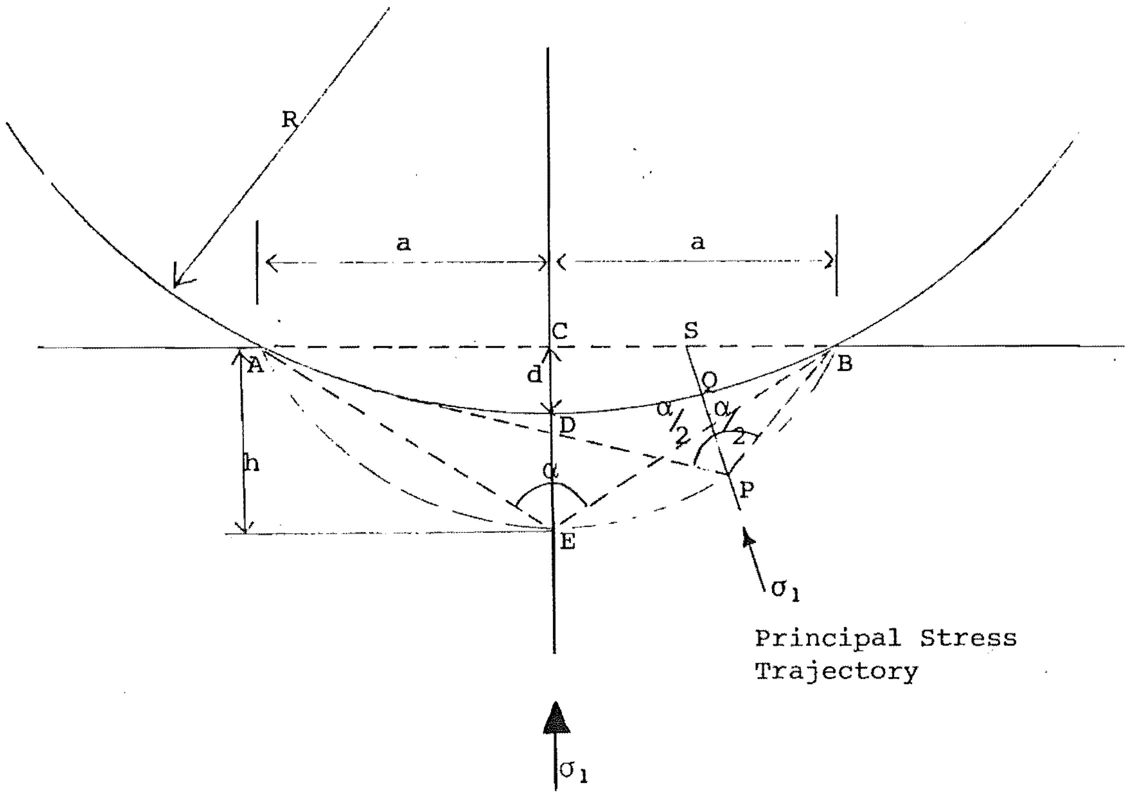


Fig. 5 - The stress system beneath a cylindrical indenter having a uniform indentation pressure.

Initially, if the indentation pressure is uniform and the material remains elastic, the analysis of Timoshenko and Goodier (1934) shows that the principal stress contours under the indenter are circles passing through the limits of contact of the two surfaces. The maximum principal stress, σ, is then given by

$$\sigma_1 = -\frac{P}{2\pi aL}(\alpha + \sin\alpha) \qquad (1)$$

When the maximum principal stress reaches the yield stress of the material, i.e. $-\sigma_y$, at the interface described by the arc subtended by the angle α_y

$$\sigma_y = \frac{P}{2\pi aL}(\alpha_y + \sin\alpha_y) \qquad (2)$$

Beneath the arc the principal stress is less than the yield stress of the material and the material remains elastic. Above the arc the yield stress is exceeded and the material is compressed to a strain ε_M. If the indentation remains small, all elements of material along a principal stress trajectory will be compressed to a constant strain ε

$$\text{where} \quad \varepsilon = \frac{SQ}{SP} \approx \frac{CD}{CE} \equiv \frac{d}{h} = \text{constant}$$

For shallow indentations $d \simeq a^2/2R$ and $h = a\cot(\alpha/2)$

The elastic-plastic boundary is then found by putting the strain above the boundary equal to ε_M:

$$\varepsilon_M = \frac{d}{h_y} \simeq \frac{a}{2R\cot(\alpha_y/2)} \qquad (3)$$

Thus the stresses within the material are given in equation (1) and the elastic-plastic boundary is an arc subtended by α_y. The Meyer hardness, H, is given by load divided by projected area, i.e.

$$H = \frac{P}{2aL} = \frac{\pi\sigma_y}{\alpha_y + \sin\alpha_y} \qquad (4)$$

If the indentation is shallow and the strain ε_M is large, as would be in an indentation test, α_y is obtuse and

$$(\alpha_y + \sin\alpha_y) \simeq \pi$$

Hence $$H \approx \sigma_y$$

To examine the validity of this analysis for wood, tests were carried out in which the yield stress in simple compression was found and the Meyer hardness was determined by shallow indentation of a steel cylinder (diameter 30mm) into the wood samples. The tests were carried out on the longitudinal radial face for both compression and hardness. The ratio of hardness to yield stress, H/σ_y, is the restraint factor, C.

Species	Yield Stress, σ_y (N/mm2)	Hardness, H (N/mm^2)	$C = \frac{H}{\sigma_y}$
P. radiata	7.44 (0.01)	8.08 (0.36)	1.09
Douglas Fir (1)	13.59 (0.81)	10.97 (0.66)	0.81
Douglas Fir (2)	6.02 (0.06)	7.39 (0.06)	1.23
Balsa	1.49 (0.16)	1.50 (0.07)	1.01
Kahikatea	6.08 (0.09)	6.34 (0.06)	1.04
Hard Beech	10.60 (0.18)	8.10 (0.36)	0.76
Southern Rata	36.95 (2.19)	66.20 (7.85)	1.79

Table 4 - Yield Stress, Hardness and Restraint factor for seven species of wood. Figures in brackets are standard deviations. (Yield stress determined using ISO 3132-1975).

The results show that the Meyer hardness is very nearly equal to the yield stress for species in the low to medium density range. For the extremely dense wood, southern rata, density $1274 kg/m^3$, the Meyer hardness is much higher than the yield stress. This is almost certainly due to the restraining influence of material around the site of the indentation since southern rata has much less void space than most other, less dense, cellular wood structures. For metals, the relationship between hardness and yield stress indicates a high degree of constraint within the material and the value of the constraint factor approaches 3 (Tabor, 1951). It is likely that the mechanism of failure observed in cellular foamed plastic would be very similar to the type of deformation in light wood such as balsa. It is also evident that a similar situation occurs in medium density woods of the type commonly used in construction and in some of the lighter joinery timbers. The localised deformation pattern can be seen in Fig. 6 and 7.

A further indication of the role of wood structure in determining the behaviour of the material under load can be seen from the results of loading in compression perpendicular to the grain. Consider the examples of metal in compression and wood (or any fibrous material) in compression. The failure of a ductile material such as metal is due to a movement of dislocations within the crystal lattice under shearing stress. The effect is to cause the metal to bulge, as is shown in Figure 6. On the other hand, failure of fibrous materials usually involves some form of "compression crease." If the material contains void space, the crease can involve a reduction in volume, as in the 90^{o} compression crease.

"Solid" fibrous materials must fail by a diagonal compression crease which does not involve a change of volume. (Fig. 6 (d))

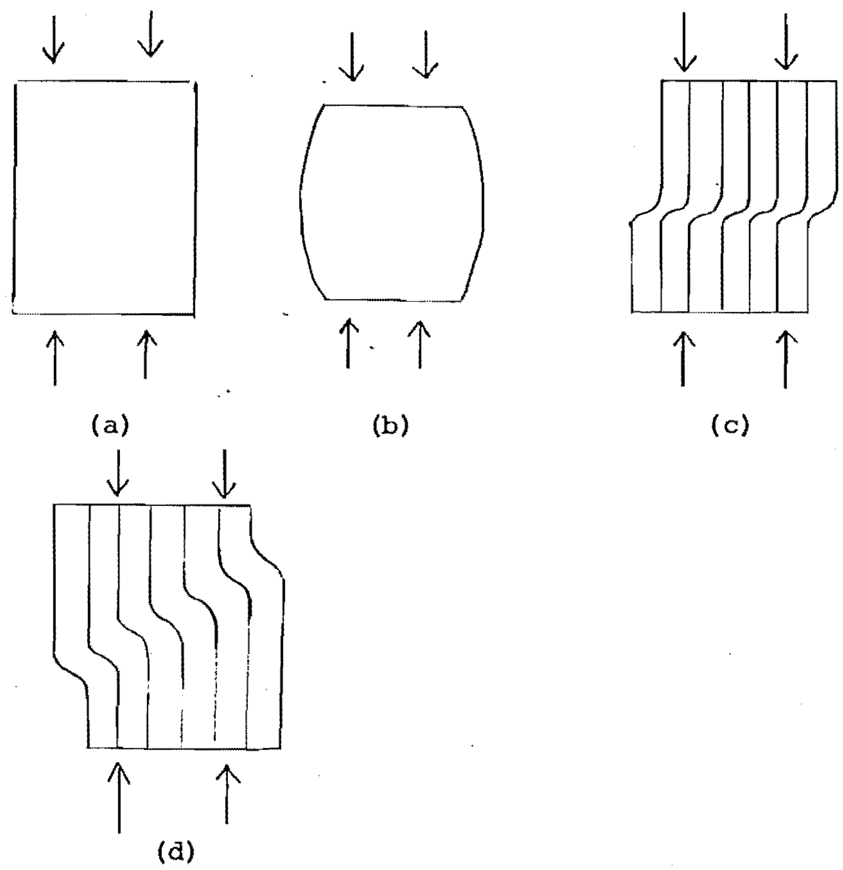
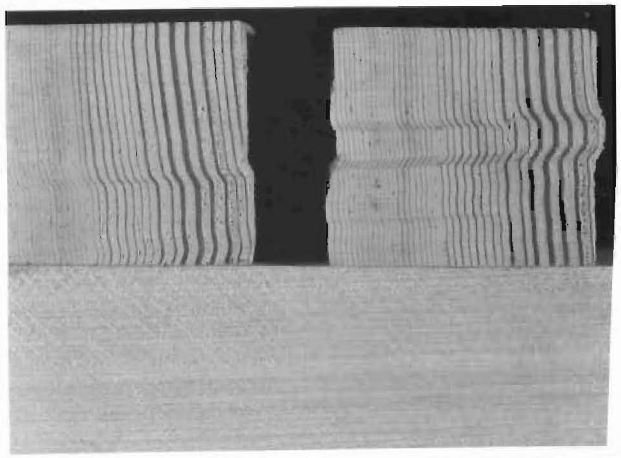


Fig. 6 - Failure of materials in compression
(a) and (b) ductile materials
(c) fibrous material, 90° "compression crease"
(d) fibrous material, diagonal "compression crease"
(after Gordon, 1978)

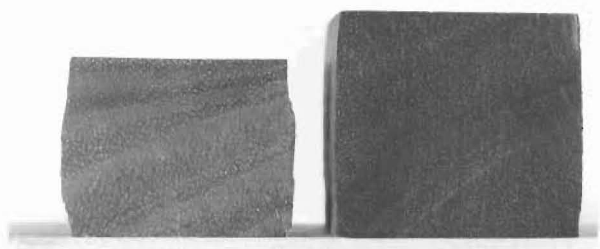
If these diagrams are compared with the actual deformation of wood samples under compression perpendicular to the grain (Fig. 7) the indication is that wood exhibits at least two, and possibly three, of these failure characteristics. Douglas fir (Fig. 7 (a) and (b)) shows distinct 90° compression creases. This is a low density wood (418 kg/m^3) whereas puriri (c) and southern rata (d) have relatively high densities (813 and 1274 kg/m^3 respectively) and less void space. Both of the denser timbers show bulging and in puriri

Section B

a diagonal crease is evident, though bulging has occurred before failure through fibre buckling. This is further evidence to suggest that wood should not be considered as a single cellular material, but as a whole spectrum of woody materials.



(a) (b)



(c) (d)

Fig. 7 - Failure of wood samples in compression perpendicular to the grain.
(a) & (b) Douglas fir 418kg/m^3.
(c) Puriri 813kg/m^3.
(d) Southern rata 1274kg/m^3.

4. INVESTIGATIVE INDENTATION EXPERIMENTS

4.1 THE RESPONSE OF WOOD TO CHANGES IN LOADING RATE

4.1.1. Background

There are many factors influencing the response of wood to loading and most of these have had considerable investigation. It is well known, for example, that direction of load application (parallel or perpendicular to the grain) is reflected in results obtained (Kennedy, 1968). It is essential therefore to standardize this when carrying out any tests. Similarly, the rate of loading is known to affect response, as wood is a material which exhibits visco-elasticity (Keith, 1972). A visco-elastic material responds to stresses by moving, under load, by the process known as creep.

The time dependent creep of wood is especially important in a loading test and it is essential to be aware of the effects of this characteristic on results. Any material which possesses creep properties (as do most materials to some extent) will react to a load by moving in such a manner that stresses may be relieved or partially relieved. This can be shown in diagrammatic form as in Fig. 8.

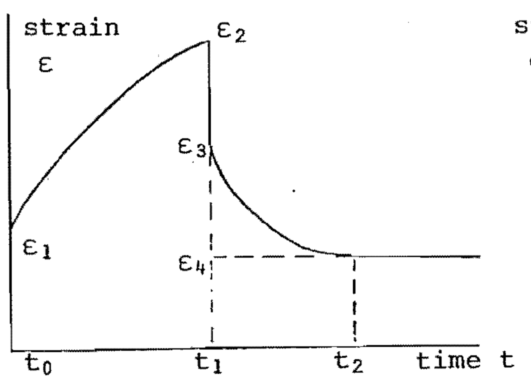


Fig. 8 - Creep behaviour of wood under constant load.

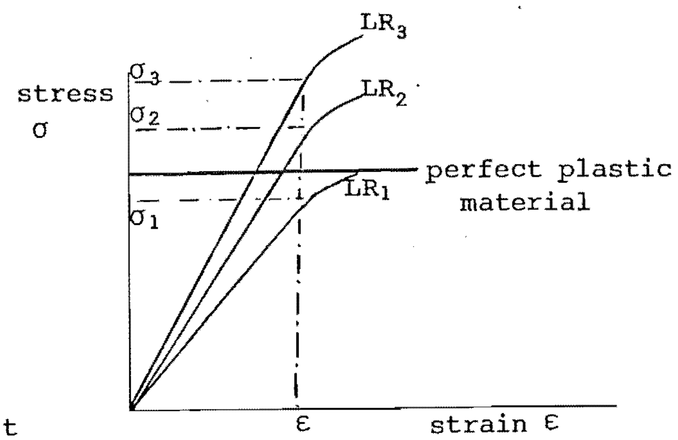


Fig. 9 - stress-strain relations as f(loading rate).

If a stress is applied at time t_o, there is an instantaneous elastic deformation, ε_1, followed by a retarded deformation, creep, under constant stress, giving an increase in strain to ε_2 at time t_1. On removal of the stress, an instantaneous recovery ε_2-ε_3, occurs followed by a slow creep recovery. After time t_2 a permanent deformation ε_4 remains and further recovery is insignificant.

The rate and extent of creep is affected not only by intrinsic properties of the material, but also by the size of the load applied, the temperature of the material and, with wood, the moisture content (Keith, 1971, 1972). For wood under constant stress, creep is proportional to the logarithm of time for approximately the first thirty minutes (King, 1961), a feature which resembles the behaviour of synthetic polymers (Gillam, 1969).

At normal temperatures of use, usually considered to be 20°C, wood creeps relatively slowly. This is extremely important in building applications and a major consideration for engineers in designing structures in which long spans of timber are subjected to loads, especially when the wood is green.

In indentation experiments, the wood beneath the indenter is subject to varying stresses depending in part on its particular position beneath the indenter. The fibres nearest the tip of the indenter experience the highest strains, while those further away may only be elastically deformed. The precise stress-strain configuration at any point is also determined by the rate of loading. When testing for hardness, loading rates as low as 0.5mm/min. and as high as 6.6mm/min. are recommended, depending on the standard being followed. As the indenter is driven further into the specimen, at constant rate, the strains experienced at any point increase with time. The concomitant stress changes at a rate determined by the resistance of the wood to deformation. This characteristic is derived from a wide spectrum of retardation or relaxation times.

The physical picture is one of numerous complicated molecular adjustments taking place when the stress is applied, such as microfibril chain-chain slipping and uncoiling of fibres, each of which has its own relaxation time. If the loading rate is very low the creep rate may become comparable with the loading rate. Because the creep induced strains are increasing at a rate similar to the loading rate, incremental plastic deformation will occur without requiring an increasing load to maintain the constant rate of indentation. Conversely, at a higher loading rate, a higher stress would be required at the same indentation depth in order to strain the wood enough to produce plastic deformation. In terms of Fig. 9 the stress required to produce a strain ε_1 increases with increasing loading rate.

Murase and Ota (1972) show that, in an indentation hardness test, the wood is likely to creep at rates comparable with loading rates if the loading rate is less than 5.0mm/min. This does not mean that any test carried out using lower loading rates are invalid. A study at lower loading rates would be analogous to the work of Atkins, Silverio and Tabor (1966) on metals where a relationship was found between the permanent indentation size and indentation time which was directly related to the creep behaviour of the metal. Murase and Ota pressed spherical indenters of different diameters into wood to a load of 10kg at speeds varying from 0.5 - 100mm/min. and noted that the depth of indentation at that load decreased as loading rate increased. The effect of ball diameter for a given loading speed is to decrease the indentation depth required to reach the specified load as the ball diameter increases. (This is considered in more detail in a later section). The depth-load relationship is much more sensitive to loading rate changes at very low speeds (below 5.0mm/min.) and particularly for smaller balls.

If a simplified picture of the deformation occurring under the indenter is considered, the resistance to chain slipping is loading rate dependent and so determines the relative amounts of elastic and plastic deformation occurring. If the wood is loaded rapidly, a smaller proportion of the strains occurring will be plastic, at least at any given load. Consequently, there will be a large elastically deformed region and the elastic-plastic boundary will be closer to the indenter. The interchain bonds within wood, and their time dependent slip characteristics, have the effect of increasing the yield stress of the wood as rate of loading increases. Inevitably, much larger strains are possible under rapid loading before plastic deformation, allowing large elastic strains to occur. This would not be the case, of course, in a perfect plastic material, in which the yield stress of the material would remain constant.

4.1.2. Experimental

In order to determine the effect of the loading rate in hardness tests using wedges, a series of tests was arranged in which samples of *Dacrycarpus dacrydioides* (kahikatea) were loaded at different speeds using a wide range of wedge angles.

Crosshead speeds were chosen to include both very slow, creep dependent response as well as rapid deformation response of the wood, of the type associated with the current Janka hardness test. Speeds of 0.01, 0.1, 0.5, 1.0 and 5.0 mm/min. were used.

Wedges of included angle 30°, 45°, 60°, 90°, 105°, 120°, 136°, 150°, 160° and 170° were indented into the radial surface of specimens from a piece of kahikatea of uniform density (475 kg/m^3). All the tests were made under controlled conditions of 20°C and 55% relative humidity. This gave a moisture content of approximately 13% for this species. The wood had been stored in this environment for six months.

The samples were machined accurately to achieve the desired grain orientation and were surface sanded with a fine grit paper to finish. Samples with knots or any other visible defects were discarded without investigation. All the wedge indentations were carried out on samples 20mm wide and 20mm deep. Care was taken to ensure that tests were kept well apart (>30mm) and away from the sample ends (again >30mm).

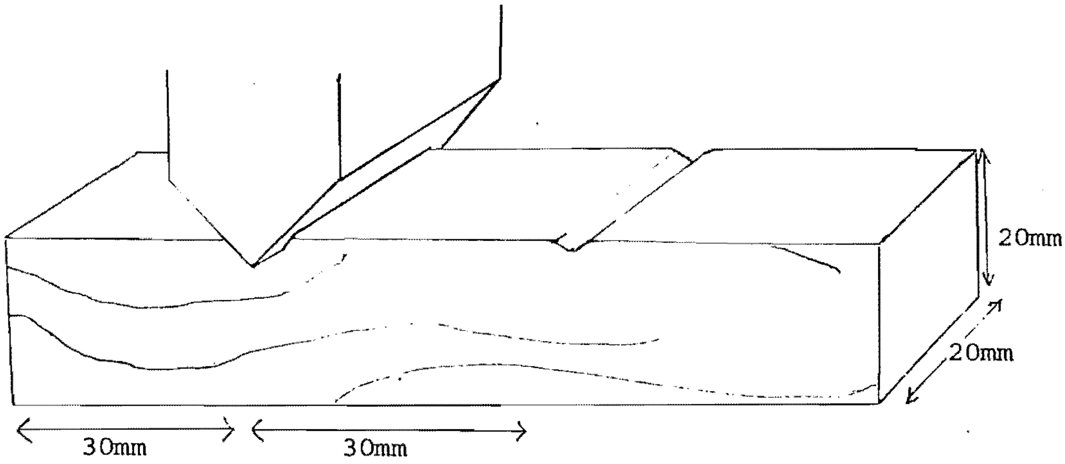


Fig. 10 - Positioning of sample for testing

There were four replications for each angle at each speed and results are shown in Appendix A and plotted on Graph Fig. 11.

From the outset it was suspected that a cutting mechanism of failure would occur if the wedge angle was below a certain value. Janka (1906) rejected the wedge on the basis of this in his experimental work in search of a good hardness test for wood. His wedge, which resulted in a $1cm^2$ projected area of contact, was embedded so that all four edges penetrated the specimen, causing shear of the wood fibres at either end of the tool. In our experiments, the tool is wider than the sample and no edge shear is involved. Further, Janka used only a 30^o wedge which is far too sharp and is proposed in this report as a cleavage testing tool rather than for the testing of hardness. His approach was clearly unsatisfactory and in no way invalidates our experimental technique.

The cutting mechanism at the tip of the tool is apparent for all the indenters of less than 90° (i.e. 30°, 45°, 60°) and for this reason they cannot be considered as measuring the true hardness of wood. Tools having included angles of 90° or greater gave an initial nominal hardness that remained constant until the depth of penetration was such that the bent fibres beneath the indenter began to experience microfailure. This occurred immediately with the sharper indenters, whereas for the 90° indenter this was at a depth of about 2mm.

The effects of angle, indentation depth and loading rate are shown in the graphs Fig. 11 and Fig. 12. An analysis of variance on the data for the loading rate and wedge angle shows that any change in either variable will have a significant effect on hardness. (See appendix).

It has been suggested that the wood is relaxing under the indenter during indentation and provided the indentation rate is slow enough. Murase and Ota (1972) examined this effect in their tests on *Chamaecyparis taiwanensis* (Taiwanhinoki) loaded by steel spheres of different sizes (diameters 6.35, 12.7, 19.05, 25.4mm). They found that for a 10kg load a greater depth of indentation could be reached at lower penetration rates especially where the rate was below 5mm/min. This effect was more marked for smaller ball diameters and also with increased moisture content of the wood.

The load/time plots obtained from the tests were analysed to find the relationship between nominal hardness and depth of indentation. Generally, hardness is constant

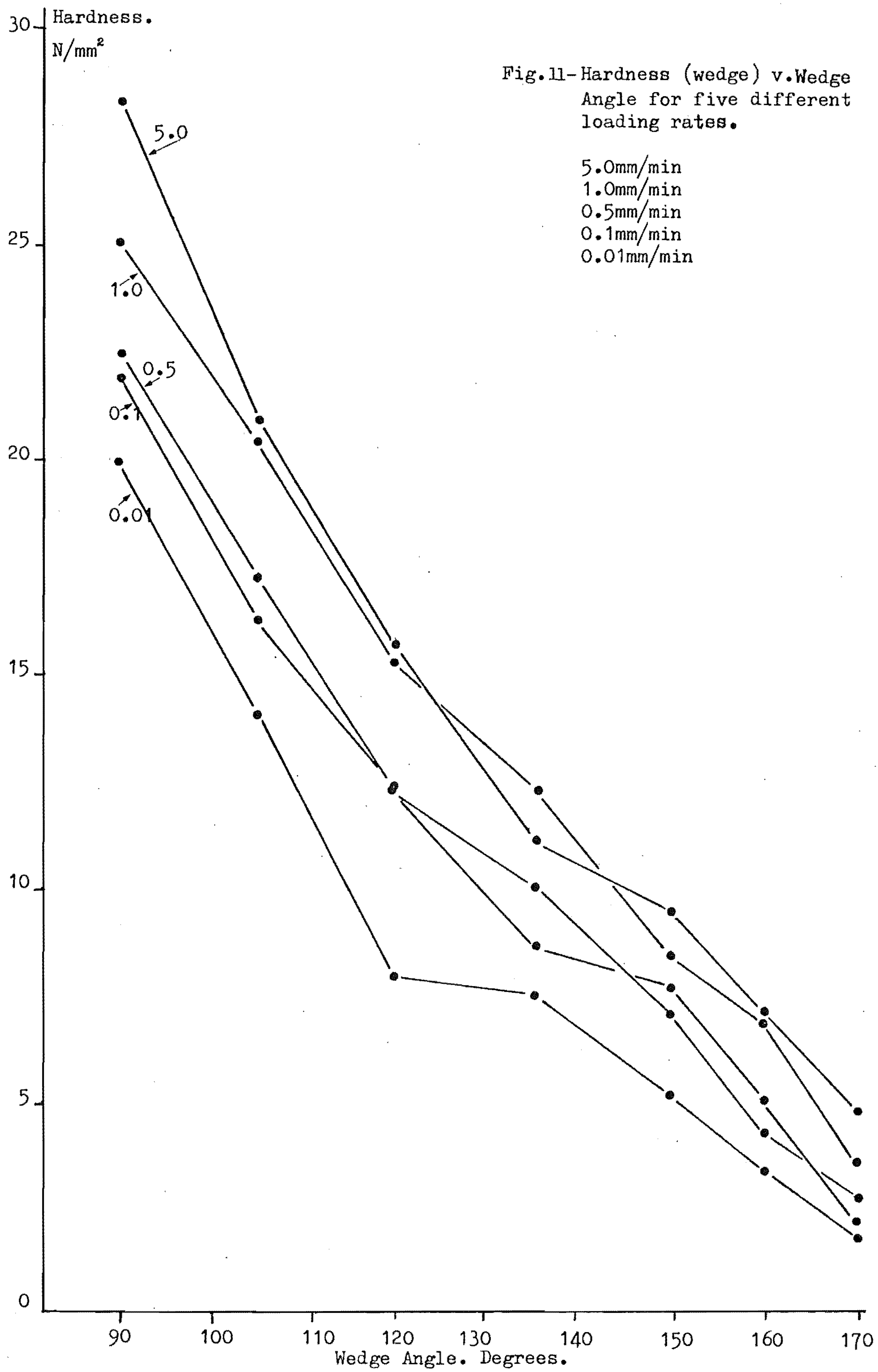


Fig.11- Hardness (wedge) v.Wedge Angle for five different loading rates.

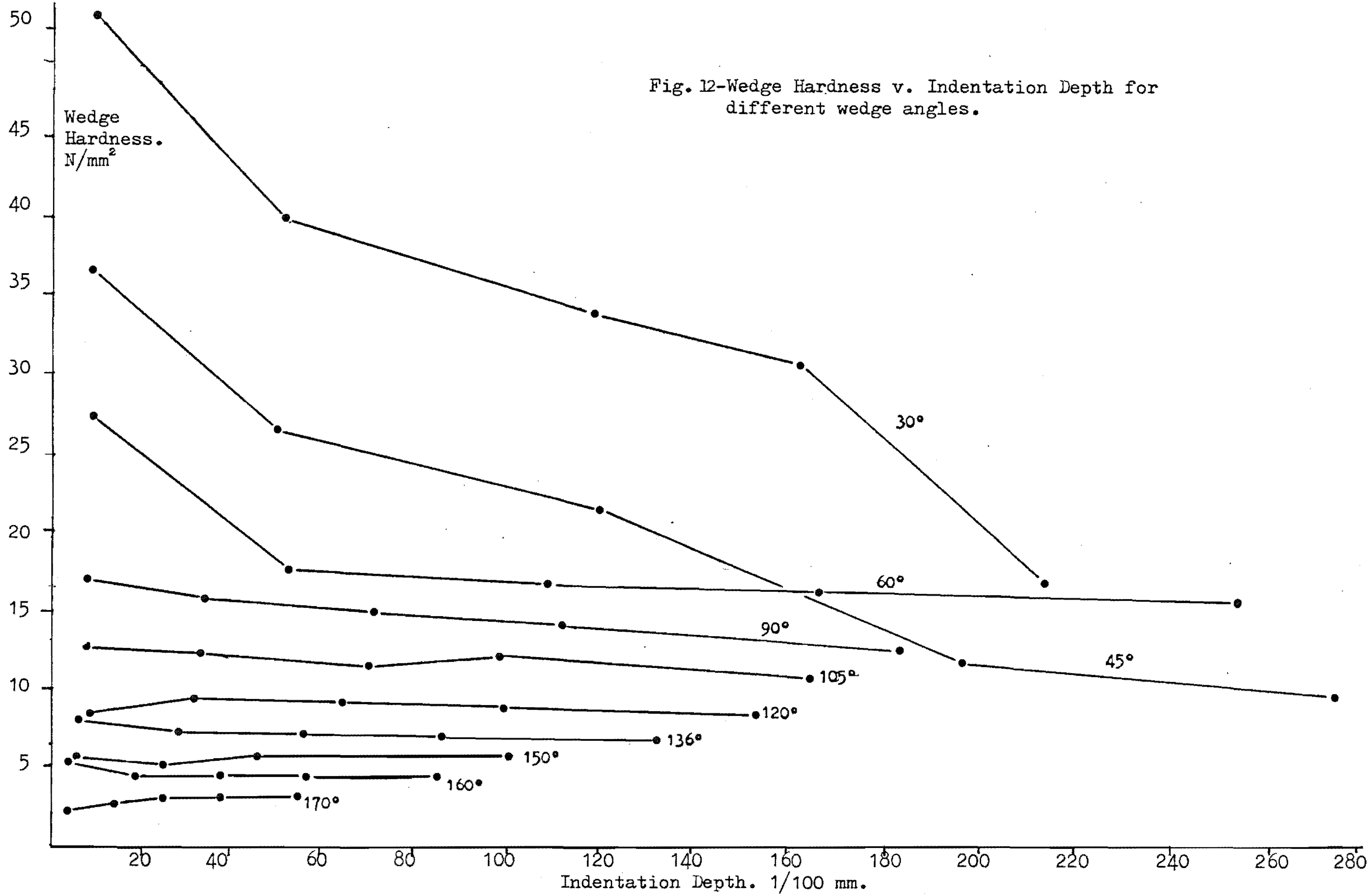


Fig. 12-Wedge Hardness v. Indentation Depth for different wedge angles.

for a large range of indentation depths, with the following exceptions.

For 30°, 45° and 60° included angles, the nominal hardness falls off rapidly as depth increases. At 30° and 45°, penetration involves cutting of the fibres. Deformation of fibres in terms of crushing or bending is limited and localised to regions very close to the indenter side surfaces. There is very little deformation of fibres below the indenter tip. (See Fig. 14). In the 60° indentation, the cutting effect is still present, but there is a definite area of crushing to either side of the indenter and a small, but detectable, deformed zone a small distance underneath the tip.

For the sharper obtuse angles, especially 90° and 105° there is a marked tendency for microfailure to occur in the wood causing the load to fall off. This is indicated by small, rapid drops in the required force to maintain the crosshead speed and is accompanied by audible fracture noise manifest in a sawtoothed, rising force/penetration curve which gradually becomes less and less steep. There is no evidence of cutting with any indenter of angle 90° or greater.

Compression of the fibres at either side of the indenter apex is common to all angles. The maximum distance away from the apex line at which permanent deformation is easily detected after indentation is approximately equal to the contact semi-width in all cases.

High strains are produced under the sharp indenters and are sufficient to cause permanent deformation within the fibres. At larger included angles strains are less severe, but closer to the indenter where strains will be larger, some plastic deformation occurs, becoming less evident as the included angle of the wedge increases. As can be seen from the photographs, the permanent deformation is almost negligible for the 170° indentation. In progressing from 170° to 136°, the plastic deformation zone beneath the indenter becomes deeper. From 136° - 90°, it is increasing in depth but progressively narrowing as 90° is approached. For the 60°, 45° and 30° indenters, the plastic deformation beneath the indenter decreases, and most of the permanent damage is in the form of severed fibres where the sharp tip of the indenter has cut into the wood. With the 30° indenter it is obvious that virtually no other type of deformation other than cutting occurs.

The deformation underneath a wedge shaped indenter can be explained as follows. With any wedge angle, the highest strains are close to the indenter, becoming less as distance from the indenter increases. Excluding the indenters which produce cutting, plastic deformation decreases with decreasing strain until at a distance away from the indenter strains will be very small and mainly elastic. The theory of elastic-plastic behaviour, that is when both elastic and plastic strains are involved in deformation, is highly complex. Even in solid materials such as metals, which have been thoroughly investigated, this analysis is extremely difficult because of the unknown and changing shape of the elastic-plastic boundary. Johnson (1971) has shown that for wedge indentations in solid perfectly plastic materials, the hardness is governed by a single parameter

$$\frac{E}{Y}(\tan\ \beta)$$

where E is the elastic modulus and Y the yield stress in compression. For a wedge of included angle 2α, $\beta = 90-\alpha$.

This analysis is valid for β values to 30° (120° included angles). For sharper angles the deformation mode is different and the above parameter is no longer valid (Hirst and Howse, 1969). It is likely, too, that for a cellular material such as wood, the above analysis could not be applied with any confidence since the assumptions are based on a mechanism which can only operate in a rigid, perfectly plastic, incompressible medium (Johnson, 1971).

The best analogy would be to assume that wood behaves as a cellular foamed plastic. It has already been shown (P. 41) that for very small strains the hardness is approximately equal to the yield stress of the material, indicating that wood and cellular foamed plastics do behave in a similar manner.

With a wedge indentation, the high strains close to the indenter appear to form a cap of plastically deformed material which then approximates a cylindrical indenter. This can be seen in the photographs on Pages 65-8. It would then be reasonable to assume that the stress contours around this cap would be similar in shape to those underneath a cylindrical indenter. This suggests that the analysis for wedges would not differ greatly from the approach used by Wilsea *et al* (1975) especially for small indentations.

The distribution of stresses underneath a wedge shaped indenter has been shown by Hirst and Howse (1969) for perspex. When the material is under load, the profile of its surface is identical with that of the indenter. When the load is removed the recovered indentation will be shallower and the difference can be used to calculate the distribution of stress under the indenter on loading.

Four regions of operation of different indentation mechanisms were identified.

(i) For wedge indenters of high apex angle the stresses underneath the indenter are higher towards the indenter tip. In this case, or in the case of a highly elastic material, the mean stress measured experimentally falls below the elastic mean stress by an amount which depends on how far the elastic limit is exceeded. For a wedge of 170° indenting a highly elastic material, the elastic limit may not be exceeded and elastic recovery is total.

(ii) For sharper wedges, plastic flow occurs so that high stresses at the surface will be redistributed to become more uniform. This results in two distinct zones of plastic flow; one close to the indenter and associated with redistribution, another further away from the indenter and due to the effect of the redistributed surface stress. This is shown by Mulhearn (1959) and the mechanism is regarded as one of radial compression. Hirst and Howse conclude that the indentation pressure approximates to that for the expansion of a semi-cylindrical cavity.

(iii) For low wedge angles or materials of low elasticity the shear strength of the material is soon exceeded and deformation occurs by the mechanism for a rigid plastic solid. This means that permanent plastic deformation is dominant close to the indenter and elastic movement further away from the indenter does not occur. The material surrounding the plastically deformed zone will not yield elastically and acts as a restraining factor on the progression of strains away from the indenter.

(iv) For very elastic materials and low wedge angles, elastic recovery occurs even at relatively low angles. There is no radial compression mechanism and the deformation is one of a complex elastic-plastic nature (Hurst and Howse, 1969).

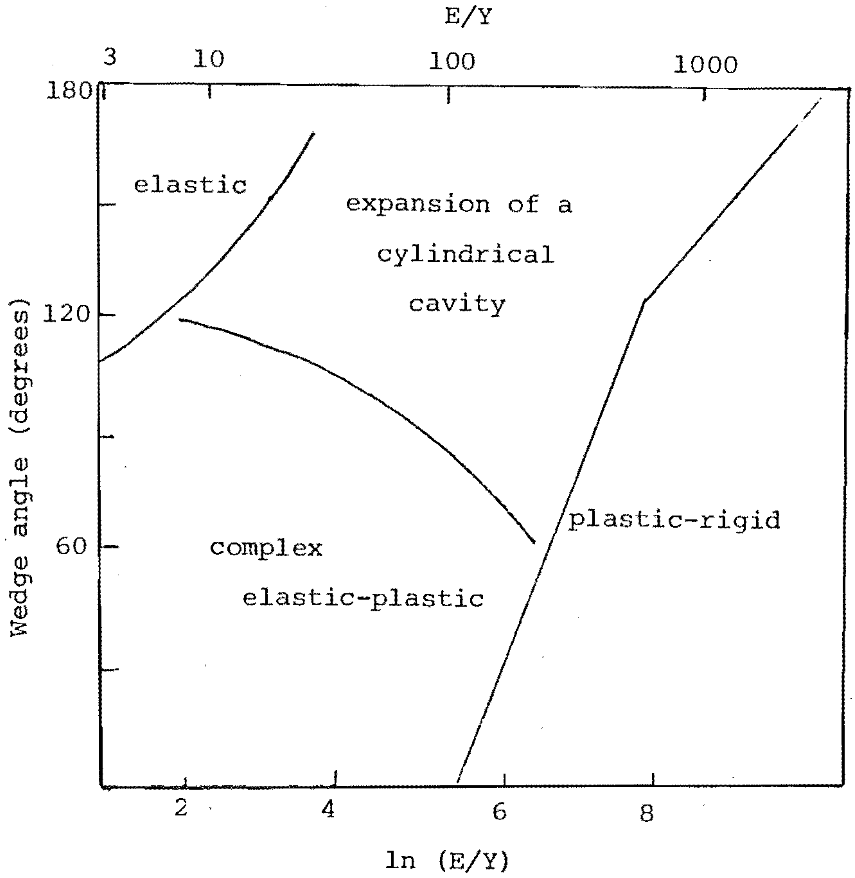
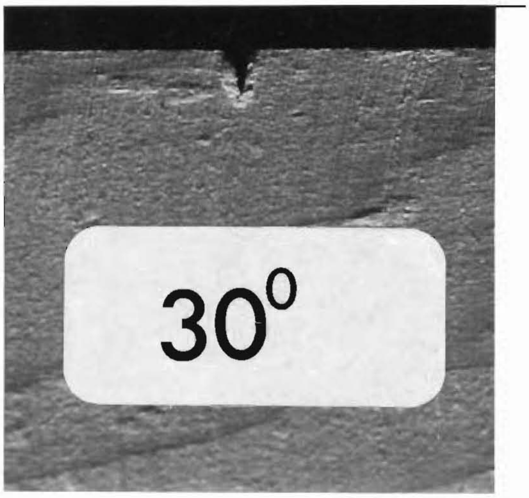


Fig. 13 - Regions of operation of the different indentation mechanisms (from Hirst and Howse, 1969).

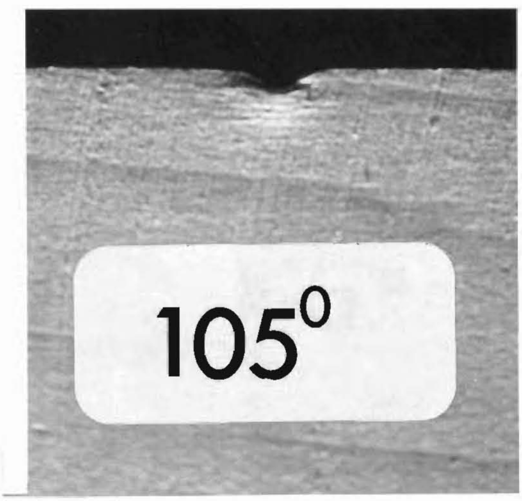
The mechanism at work in wood indentations is probably rather more complex than the possibilities described above. Certainly the deformation mode for the 170° indenter is almost totally elastic though even here it is likely that the elastic limit of the material is exceeded in a small region close to the indenter tip. The feeble impression remaining after indentation by a 170° wedge is evidence of this. For sharper wedges, plastic flow undoubtedly occurs.

By examining the loading and unloading curves for Kahikatea at different wedge angles it is evident that some of the deformation is plastic for all angles. The plastic portion of the deformation increases for decreasing wedge angle, indicating that stress redistribution, mechanism (2), is occurring, at least partially. For very sharp angles, high levels of plastic deformation occur, but some elastic strains are still present at a low level and the deformation remains complex.



(a) 30° indentation in kahikatea. Mainly cutting of fibres.

(b) 60° indenter. Plastic deformation at either side and below indenter. Cutting also occurs.



(c) 105° indenter. Significant plastic deformation below apex. No cutting.

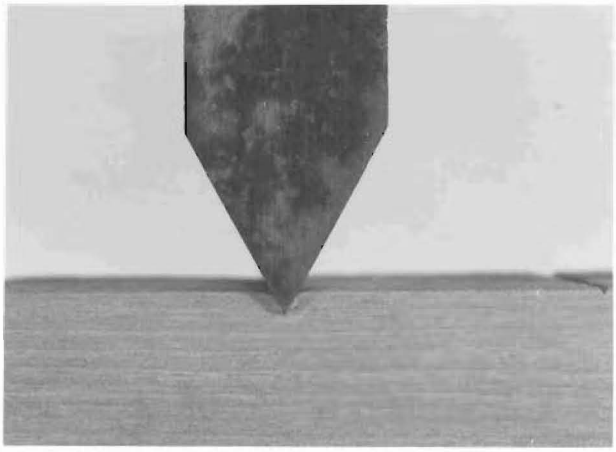
Fig. 14A

(d) 136° indentation. Plastic deformation extends 2-3 times depth of recovered indent.

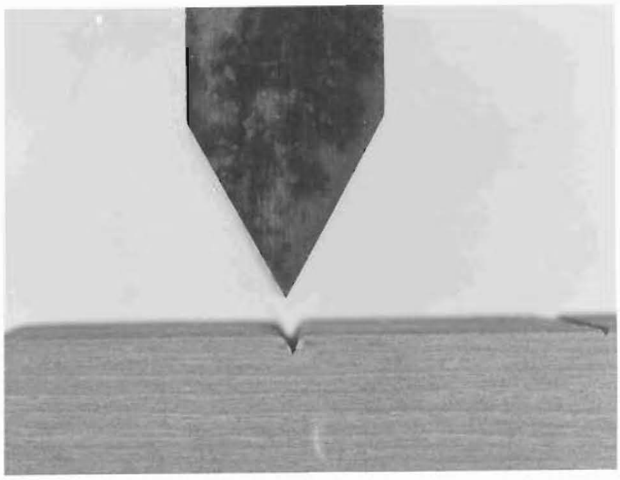
(e) 150° indentation. A similar effect to 136° indenter, though remaining impression is slight compared to total deformation.

(f) 170° indentation. Almost totally recovered, but some plastic deformation is detectable.

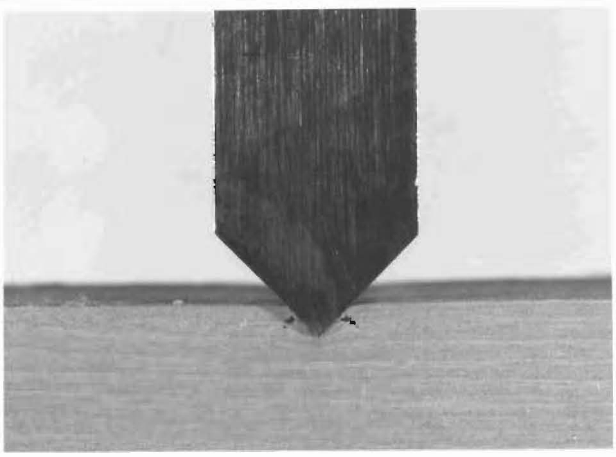
Fig. 14A



(a) 60° wedge indentation in kahikatea showing deformation at sides of indenter - little deformation below apex.



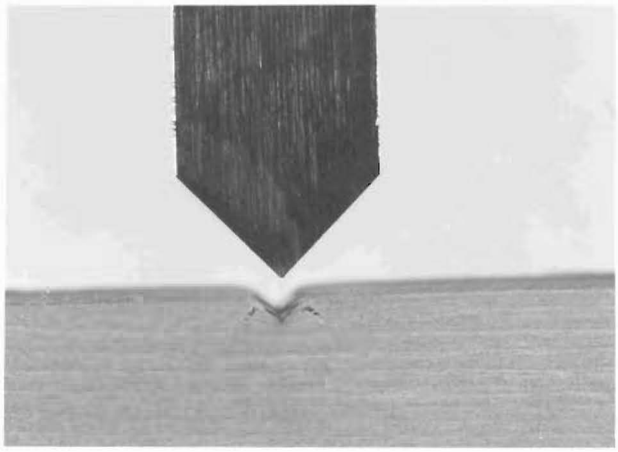
(b) Cutting effect of 60° wedge with significant plastic deformation.

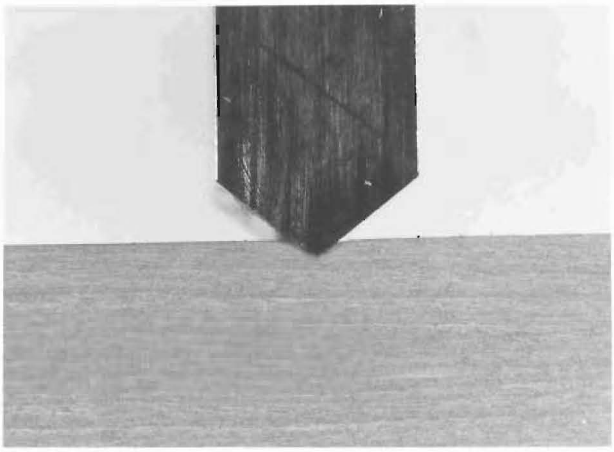


(c) Deformation of kahikatea by 90° indenter showing tensile failure of surface fibres.

Fig. 14B

(d) Remaining plastic deformation after removal of 90° indenter. No cutting, but more noticeable compressed zone below apex.





(e) 105° indentation of kahikatea. Bending of fibres is apparent and deformation zone deepens below apex.

(f) 120° indentation of kahikatea. The situation is similar to the 105° indenter though strains are less severe and the compressed zone beneath the apex is deeper.

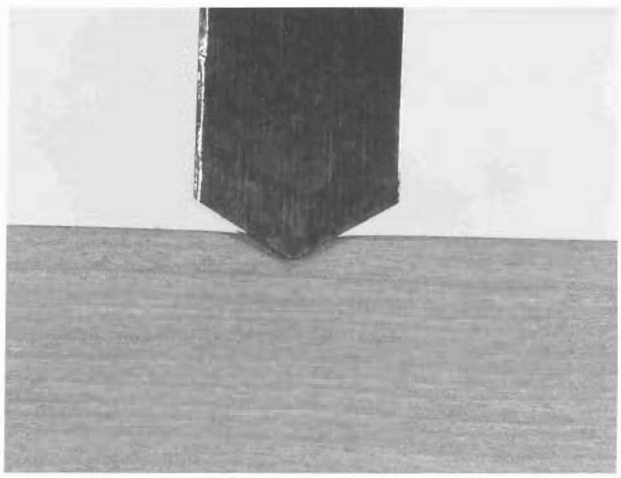
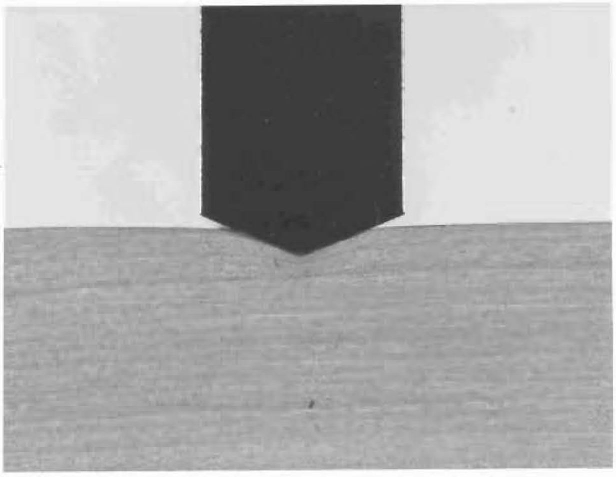
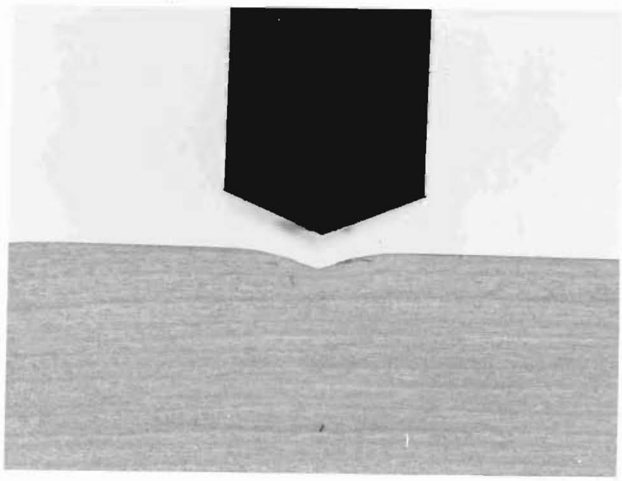


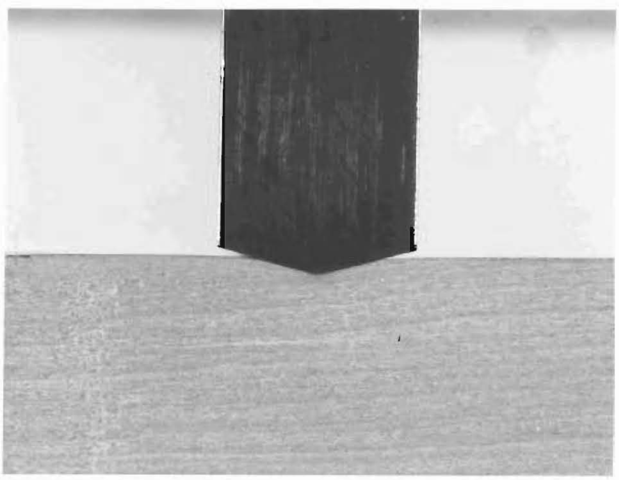
Fig. 14B



(g) 136^{o} indentation of kahikatea. Strains below the apex visibly extend about half the depth of the indent.

(h) On removal of 136^{o} indenter a fairly deep plastic deformation zone is evident.

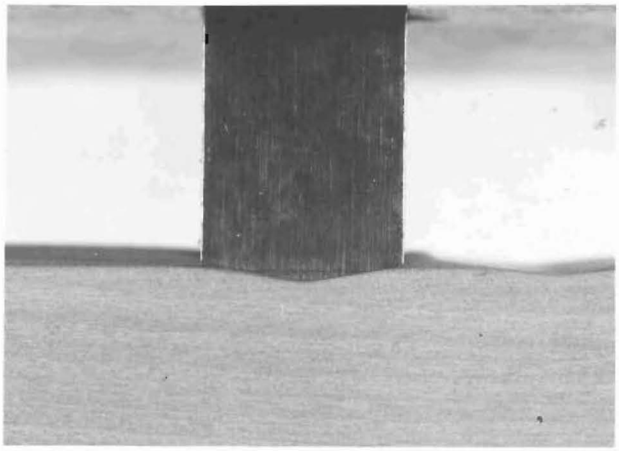


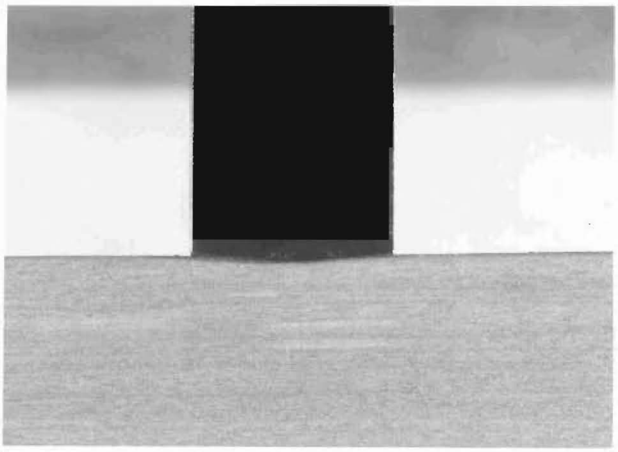


(i) 150^{o} indenter shows only compression and slight bending of fibres.

Fig. 14B

(j) 160° indenter. A similar situation to 150° occurs. Strains are very slight though still sufficient to cause plastic deformation.





(k) 170° indenter. Strains are slight, but a compressed "cap" is evident below the whole of the indenter.

(l) Strains were sufficient to cause some plastic deformation. Possible evidence of shear failure at limit of indenter.

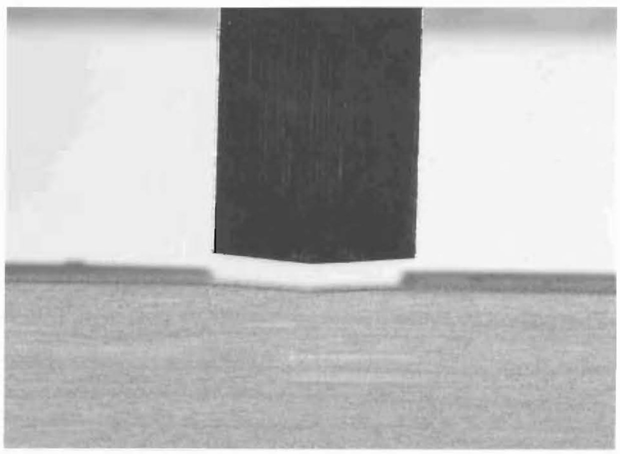


Fig. 14B

4.2. INDENTATION DEPTH

Hardness as a characteristic associated with the integrity of the medium under test, and hardness should be measured at a point before fibre failure occurs. Hadfield (1916) concluded that the sense of softness or hardness is gained whilst the local compression is being applied and not necessarily by any secondary evidence such as the dimensions of the indentation after loading. He suggested that the yield point was all that needed to be measured. A practical point against large depths of penetration would be the time taken to perform the test. The larger the indentation depth, the faster the tool must be embedded in order to retain the convenience of a rapid test. For example, the Janka Ball test takes less than one minute at its specified speed of 6.6mm/min. If the Japanese standard test speed of 0.5mm/min. were to be used, the Janka test would take approximately ten minutes to execute.

The Japanese test (JIS Z 2117-1977) standardises the indentation depth of $^1/\pi$ mm or about 0.316mm. This makes the duration of the test again less than one minute, and with this degree of penetration it can be considered a true hardness test.

The rate of 6.6mm/min. used in the standard Janka test (ASTM D143-52) is considered by some to be too high. (Miyajima, 1969). This high speed test results in catastrophic failure of fibres underneath the indenter, even early in the test. Unfortunately the excessive penetration depth required (5.642mm) precludes the use of a much lower speed because of the need for a test of reasonably short duration. Additionally, a high penetration is likely to measure more than true hardness, indeed, a considerable amount of failure of fibres occurs before the full indentation depth is reached. In some cases load is actually decreasing as maximum indentation depth is approached. (See graphs pages 71 and 72).

In the Janka test, the depth of penetration was chosen arbitrarily. A ball of radius 5.642mm conveniently gives a nominal contact area of $1cm^2$ if it is embedded to half its diameter. Consequently a load applied, in kg, will be of the same magnitude as the hardness in kg/cm^2. However, if hardness is to be a measure of the properties of the undamaged fibres close to the surface of the wood, then the result becomes invalid as soon as the fibres fail. If the hardness test does test the fibres to destruction then the ultimate hardness must be regarded as the hardness measured immediately prior to failure.

Indentation depth must be regarded as an important factor to be decided upon after consideration of its effect on the results of the test. To choose an arbitrary, if convenient figure, as Janka has done, can add undesirable influences. A more reasonable indentation depth, for a ball type test such as Janka's, is the $^1/\pi$ mm used in the Japanese standard. A further problem discussed by Sunley (1965) is directly accountable to the excessive penetration in the Janka test: with dense wood samples it is impossible to test hardness according to the standard set because the wood splits before full penetration is achieved. For dense woods the Janka test cannot be used for hardness measurement. Similarly, for soft timbers such as Balsa, the load is decreasing long before the required depth of indentation is reached and the hardness derived from the Janka test is lower than it would be if a hardness value were to be calculated from the load at a lower penetration. See Fig. 17 and 18.

In order to alleviate some of the problems resulting from excessive penetration depth, it is proposed that a wedge shaped tool be used to test the hardness of wood. The main advantage of the wedge over the ball is that impressions are geometrically similar at any penetration depth and so the hardness value should remain dependent on the properties of the wood and not the geometry of the indenter. Thus, any penetration depth will give a comparable hardness value for a given material - a notable shortcoming of the Monnin cylinder test is its lack of geometric similarity giving hardness results which are different for the same timber at different penetration depths. Additionally, the wedge overcomes the problem of the anisotropy of wood, since it is, in effect, producing an impression in one direction only, whilst still covering a reasonable area of wood to account for local variations in structure. The proposal is to investigate the wedge hardness on the radial face, the reasoning being the same as that given on p.17 for the Monnin Test. However, investigations will be carried out to determine the effect of orientation of sample with respect to indenter, as well as investigations into the Wedge Hardness of cellular foamed plastics.

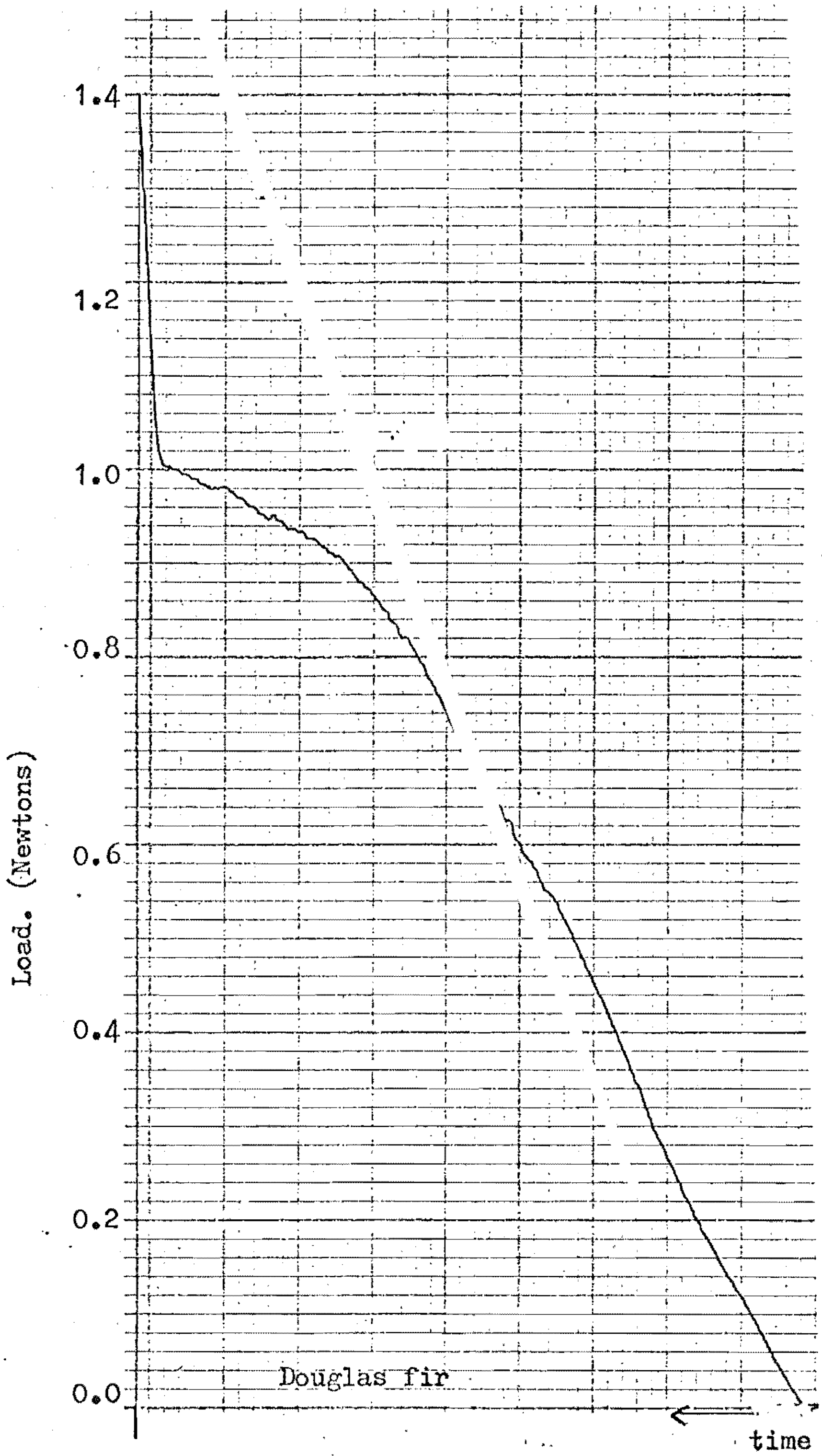


Fig. 15 - Load versus time for Janka indentation of Douglas fir.

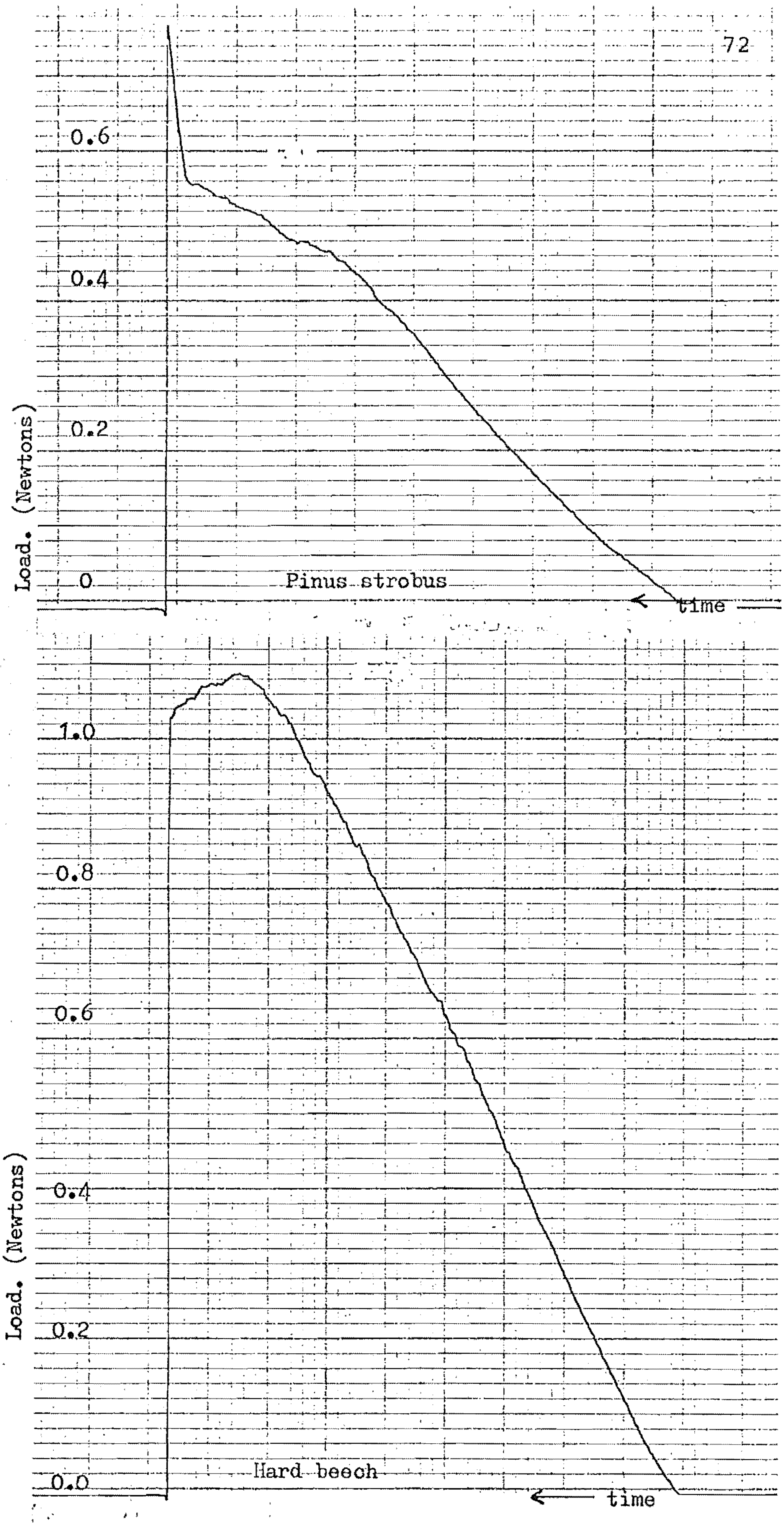


Fig. 16 - and
Fig. 17 - Load versus time for Janka indentations of *P. Strobus* and Hard beech.

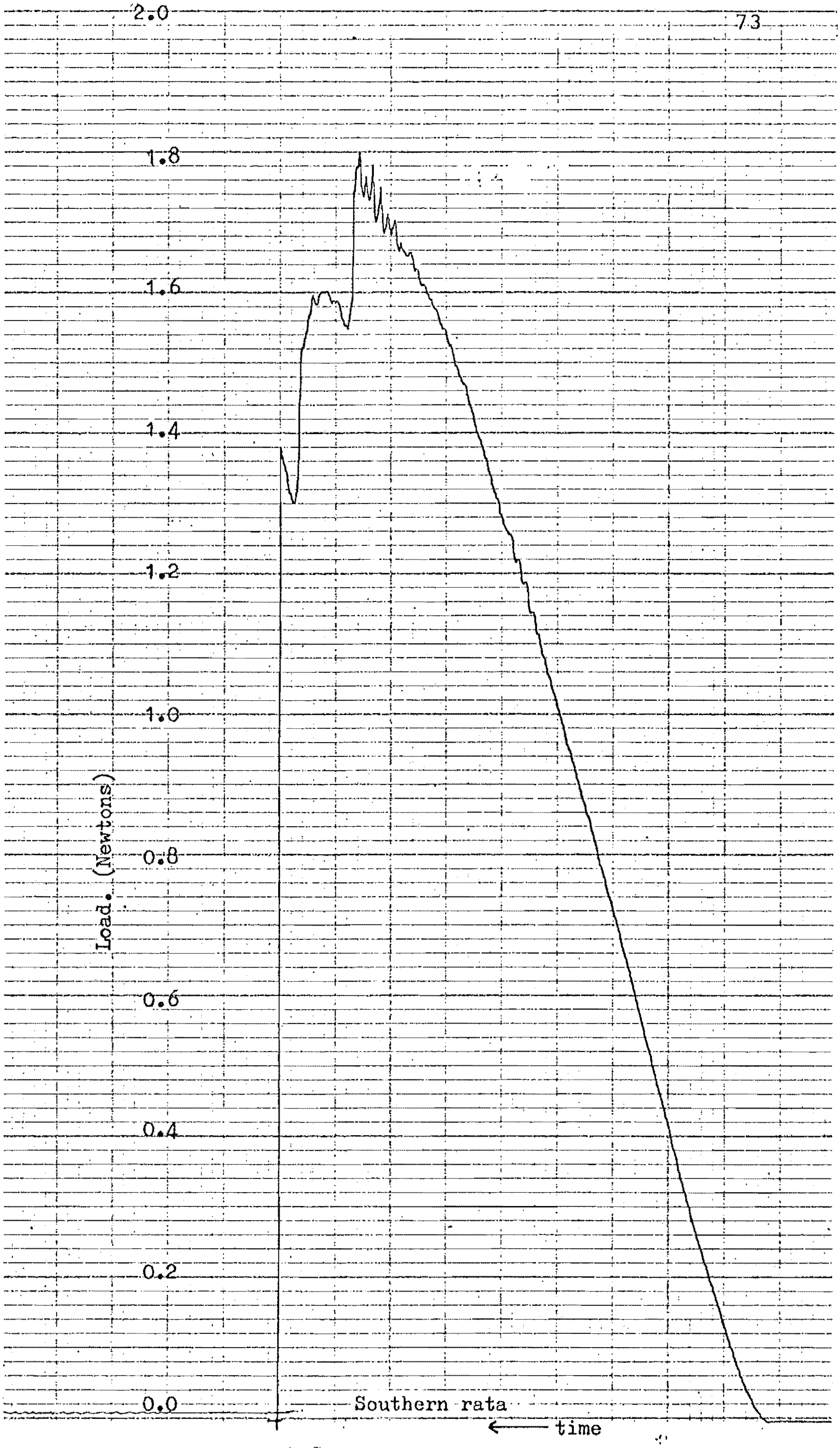


Fig. 18 - Load versus time for Janka indentation of Southern rata.

4.3. INDENTATION OF FOAMED PLASTICS

To give an indication of how cellular materials other than wood might react under indentation loading, polyurethane foams in a variety of densities were tested. The foams were manufactured on request by Messrs Foam Engineers of Christchurch. The process involved the mixing of two resins in a confined space, the volume of the initial components determining the density of the final foam. Eight different densities were obtained ranging from 284.9 kg/m^3 to 1578.2 kg/m^3. The foams obtained by this method give a random cellular structure as opposed to the ordered anisotropic cellular structure of wood. However, the density variations within each foam were very small (maximum 8.16% for foam G, density 1000.8 kg/m^3), density being determined from six 20mm cubes from each sample. Surprisingly, the less dense foams show least variability. In the manufacture of polyurethane foams there is often elongation of cells in the direction of rise leading to anisotropy. This can cause the foam to exhibit different strength properties in different directions, for example, there may be 25-30% difference in compressive strength. (Ferrigno, 1963). In addition, there is a tendancy for bubbles to rise in the mix during manufacture making the final structure more irregular. Normally the bubbles will form dodecahedral cells as a result of packing of bubbles and uniform distribution of stress. In reality, the stresses do not distribute themselves evenly as is evident from the appearance of many hexagonal and pentagonal cells. (Ferrigno

1963, P. 90). Generally, foamed cellular materials of this type are far from perfect, but, unlike wood, all cells have a structural similarity.

It is necessary to define the nature of a foam in terms of flexibility or rigidity. An ASTM subcommittee (D11-22) defined a rigid foam in the following manner:

> A rigid cellular material is one which will rupture when a specimen 20 x 2½ x 2½cm is bent around a 2½cm diameter mandrel at a uniform rate of one lap in 5 sec and at a temperature of 15-25°C.

A flexible material would not rupture in this test, which means that all cellular materials are either rigid or flexible, with no semi-rigid or intermediate classification. This definition does not appear to be strictly adhered to - most literature accepts the existence of semi-rigid foam. However, the polyurethane foams used in this work are classified as rigid, and flexible foams are not considered further.

There are approximately 60 ASTM standards relating to mechanical properties of cellular materials and of these about half are applicable to rigid foams.

The main ones, to be considered here, are as follows:

ASTM D1621-73 (1973). Measurement of apparent density of cellular materials.

ASTM D1622-63 (reapproved 1970). Measurement of compressive strength of cellular materials.

ASTM D1623-72 (1972). Measurement of tensile strength of cellular materials.

ASTM D732-46 (reapproved 1969). Measurement of shear strength of plastics.

Extensive testing of the foams was not carried out, except in terms of testing of the hardness of the foams. The American Society for Testing and Materials specifies four standards which may be applied to rigid cellular foams. These are:

ASTM C367-57 (1978). Strength properties of prefabricated architectural acoustical tile or lay-in ceiling panels.

ASTM C569-68 (1975). Indentation hardness of preformed thermal insulations.

ASTM D785-65 (1976). Rockwell hardness of Plastics and Electrical insulating materials.

ASTM D2240-75. Rubber property - Durometer hardness.

C367-57 (1978) requires that a 2in. diameter ball be embedded to a depth of 0.25in. below the original surface at a rate of 0.1in/min. and the load recorded in Newtons is the hardness of the material.

C569-68 (1975) requires that a 1in. diameter ball weighing 2lb be allowed to rest on the surface of the material and then a load of 10lb be added. The increase in penetration, in inches, is recorded after 30 seconds giving a hardness indication.

D785-65 (1976) is a test for plastics based on the Rockwell method. The procedure follows one of two set patterns.

Rockwell A procedure gives a hardness number derived from the net increase in the impression depth as load is increased from a fixed minor load to a major load and then returned to the minor load.

The Rockwell B procedure involves increasing the load from a fixed minor load to a major load and measuring the change in penetration. The Rockwell numbers are always quoted with a scale symbol representing indenter size, load and the dial scale used.

Method D785-65 is based on Methods E18, using procedure B and balls of 12.7mm, 6.35m and 3.175mm diameter and using a 10kg minor load and major load of 60kg, 100kg or 150kg.

Test method D2240-68 is based on the results of a penetration test using one of two indenters, Type A is a truncated conical indenter subtending a solid angle of 35^{o}. This is usually used for highly elastic materials such as rubber. For more rigid materials, Type D indenter is used. This is a rounded tip cone of solid angle 30^{o} and with a tip radius of 0.1mm. Hardness is reported as a penetration achieved under specified conditions of loading.

In the following reported tests, the Janka C test is very similar to C367-57, but the purpose here was not to evaluate the current tests for foams. These tests were carried out in an attempt to link the characteristics of two cellular materials, wood and foam.

Indentations were made using wedge tools of different angle ranging from 60^{o} to 170^{o} and with the three Janka and three Monnin tools. Details of the tools are given in Table 5 , along with the summarised results. All the tests were carried out at a crosshead speed of 0.5mm/min., at 20^{o}C and

Table 5 - Summary of Hardness data for eight plastic foams.

Key to tools: W = Wedge
MA = Monnin tool, diameter 10mm
MB = Monnin tool, diameter 30mm
MC = Monnin tool, diameter 50mm
JA = Janka tool, diameter 11.28mm
JB = Janka tool, diameter 30mm
JC = Janka tool, diameter 50mm

FOAM	A	B	C	D	E	F	G	H
Tool								
W60	2.36 (16.5)	3.68 (15.8)	3.87 (5.9	4.90 (0.2)	7.59 (2.5)	8.22 (13.0)	9.50 (15.3)	24.06 (31.5)
W90	2.07 (3.8)	2.49 (6.0)	3.62 (2.2)	3.39 (4.4)	2.95 (8.1)	7.00 (7.7)	16.59 (11.2)	29.25 (28.9)
W105	1.96 (1.5)	1.79 (9.5)	2.69 (1.5)	2.98 (1.7)	4.27 (22.7)	5.17 (3.9)	14.52 (5.5)	25.08 (34.4)
W120	1.62 (2.5)	2.11 (22.2)	2.47 (4.0)	2.29 (1.7)	4.46 (20.4)	4.59 (1.9)	11.88 (7.6)	19.72 (8.9)
W136	1.53 (0.6)	1.83 (7.6)	2.16 (0.0)	2.21 (5.4)	3.72 (5.9)	4.21 (3.6)	11.63 (11.2)	16.60 (24.3)
W150	1.24 (3.2)	1.28 (10.9)	1.90 (3.2)	1.67 (3.0)	3.11 (8.7)	3.66 (1.9)	7.41 (14.8)	12.80 (20.5)
W170	0.82 (6.1)	0.92 (4.3)	1.00 (0.0)	1.10 (0.0)	1.35 (6.7)	2.29 (2.0)	3.91 (1.3)	5.59 (7.7)
MA	1.94 (16.5)	1.63 (12.9)	2.19 (1.0)	2.52 (17.8)	2.96 (6.7)	5.92 (0.0)	6.41 (61.4)	10.17 (60.1)
MB	0.37 (10.8)	0.73 (10.9)	1.43 (32.2)	1.21 (3.3)	1.77 (7.3)	3.09 (2.6)	7.41 (4.4)	11.47 (21.1)
MC	1.51 (0.0)	-	3.32 (6.0)	-	2.54 (14.6)	-	8.61 (10.7)	16.63 (7.4)
JA	0.91 (0.0)	-	1.82 (2.0)	-	2.27 (28.2)	-	9.55 (6.7)	16.38 (31.4)
JB	0.32 (21.8)	-	1.04 (5.7)	-	3.64 (85.9)	-	7.47 (4.9)	6.03 (26.2)
JC	0.65 (3.0)	-	1.25 (6.4)	-	1.61 (8.6)	-	8.64 (12.3)	9.00 (10.0)
Density	284.9 (2.18)	318.9 (0.88)	405.3 (1.08)	456.3 (1.86)	576.8 (1.67)	654.5 (0.12)	1000.8 (8.16)	1578.2 (0.45)

Figures in brackets are coefficients of variation.

55% relative humidity, the same conditions as were used for the tests on wood.

It is immediately evident that, for a given density, these foams exhibit lower hardness values than does wood. The foams show a much smaller change in hardness values for different wedge angles when compared to wood of a similar density. Table 6 shows hardness values and their variations with wedge angle for the foams and wood of comparable density.

The structure of wood makes excellent use of materials by using high density components only where necessary so that strength is very high for a relatively low density. In contrast, expanded foam uses exactly the same material for every part of its random cell structure, presenting a matrix of much lower strength. In addition, the material making up the closed cell plastic foam is relatively brittle and fails at low strains, so that the cells collapse readily under load.

Species (density kg/m^3) \ Wedge angle		60	90	105	120	136	150	170
P. strobus	(303)	16.99	6.88	6.33	4.00	3.12	2.21	1.46
Foam A	(285)	2.36	2.07	1.96	1.62	1.53	1.24	0.82
Pukatea	(441)	24.47	18.36	13.61	10.97	9.16	7.07	4.58
Foam D	(456)	4.90	3.39	2.98	2.29	2.21	1.67	1.10
F. sylvatica	(636)	49.72	36.64	33.48	25.00	19.9	12.44	9.03
Foam F	(654)	8.22	7.00	5.17	4.59	4.21	3.66	2.29
S. rata	(1000)	142.23	116.86	100.60	70.69	53.28	41.11	14.80
Foam G	(1000)	9.50	16.59	14.52	11.88	11.63	7.41	3.91

Table 6 - Hardness values and their variations with wedge angle for the foams and wood of comparable density.

Where indenters induce very large strains, such as at the tips of the sharpest indenters, failure occurs very early in the test and this is reflected in low values of hardness. This is noticeable in the 60° and 90° wedges and especially for the denser foams. The densest foam, foam H, shows a very large degree of variability and both G and H show more variability than the lighter foams. At 1578 kg/m^3 it is likely that this is a cellular foam with very little pore-space.

An analysis of variance on the data for foams is shown in Appendix B, C and D. The data for the 60° wedge with the denser two foams, foams G and H, was anomolously low and analyses C and D refer respectively to data with the results for the 60° indenter excluded and to data with results for foams G and H excluded.

The analysis is carried out in a stepwise manner, one variable being added in each step. The computation involves the generation of a regression and a check is then made to detect how well this accounts for the variation in hardness. The significance of inclusion of each variable is shown, as well as the value of the coefficient for that particular variable and a regression coefficient (multiple R^2) for the regression equation after inclusion of each variable. The outcome of the analysis is as follows.

For the complete set of data, density is singularly the most important factor affecting hardness. The equation relating hardness and density of foams is

$y = 0.01123\rho$ y is wedge hardness in N/mm^2

ρ is density in kg/m^3

This simple relation, without an intercept constant which is added later, reasonably accounts for 71% of the variation in hardness within the 10% confidence limit. Stepwise inclusion of variables to include the intercept on the hardness axis and the effect of angle, further improve this to account for 88% of the variation. On removal of the 60° data the equation becomes

$$y = 0.00988\rho \qquad \text{(notation as above)}$$

and accounts for 78% of the variation of hardness. Inclusion of all the other variables to account for angle and intercept improve this further to 95.3% (see Summary Table C, Appendix C).

Appendix D shows a similar analysis for the foams with all angles included, but with the two densest foams, G and H, excluded. Again using the notation above

$$y = 0.00678\rho$$

this equation accounting for 84.8% of variation in hardness. Angle, intercept and hardness effects, when included in the equation together, as in Step 6, Appendix D, account for 97.68% of the variation in hardness.

Interpretation of Results

Generally, the Wedge Hardness of foamed polyurethane is dependent on density of the foam. Since both density and square of density effects are significant in the final regression it is reasonable to assume that

$$\text{Wedge Hardness} \propto (\text{density})^n, \; 1<n<2$$

However, inclusion of the grossly anomolous results for the 60^{o} indenter indicate that there is no significant angle effect - somewhat contrary to experience - and that the marginal effect detected is for a positive relationship between angle and hardness. With the data for the 60^{o} indenter removed this effect, still positive, but very small, becomes statistically significant at the 10% level. However, with this data, the interaction between angle and density is the most significant influence on hardness - as density and angle increase the interaction effect holds down the increase in hardness.

This suggests that the angle effect is strongly tied to density, but is sufficient to cause a decline in hardness as angle increases.

Data analysed with results for foams G and H removed show again that angle effect is closely tied to density changes and the overall effect of angle alone is much more significant when the accountability of the interaction term is not included in the equation (Step 2, Appendix D).

The structure of a foam is determined by the shape and geometry of the cells and also by the way in which the cells are connected to one another. However, the mechanical properties of foams are highly influenced by the type of cell making up the structure - either closed, open or reticulated cells. Closed cells generally consist of dodecahedral cavities separated by membranes of variable thickness. In open cell foams, many of these membranes are not formed and in reticulated foam materials the membranes have been removed, usually by chemical or heat treatment. (Meineke and Clark, 1973).

The compressive stress-strain properties of this type of material appears to be a function of the proportion of open cells in the material. Reubens and Skotchdople (1965) show that a semi-rigid closed cell foam becomes completely flexible by perforation of the membranes. In the same work it has been shown that physical rupturing of closed cell foam markedly reduces compressive strength and compressive modulus. Reubens and Skotchdople point out the importance of resistance to airflow in a cellular material, cell membranes being the main impediment. The effect of this is to make compressive stress strain behaviour of closed cell materials extremely rate dependent. It has been reported that the permeability of green wood may be improved by dynamic compression rolling (Cech and Goulet, 1968). This may be the result of a mechanism similar to the rupturing of cell membranes in foams under compression, as described below. Microscopic examination indicated no breakdown of the cell walls but the pit membranes were seen to exhibit splitting (Cech, 1971).

It is possible that a closed cell foam may be weaker than an open cell foam even though it may be less dense. When membranes of closed cells are stressed through loading, tensile deformation occurs and the membrane may break at very low loads or strains. The crack may then propagate easily into the strands of the cell wall. In open cell materials the strands are flexed, but will not readily break. Thus closed cell foams may be stronger in compression only until failure occurs in a cell membrane. The diagrams show simply the effect of compression in foams and tearing of cell membranes.

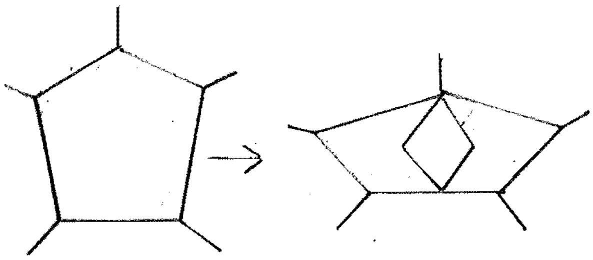


Fig. 19 - Deformation and rupture of membranes during the compression of foams.

This type of insidious failure is analogous to the development of shear failure in wood cells as reported by Dinwoodie (1971). Application of stress to the wood causes micro-shear failure which eventually propogates through the whole cell and initiates failure. However, the complex interlayering of wood cell walls, along with the cementing effect of the lignin in the matrix, gives wood a variety of pathways through which stress and strains may be absorbed, resulting in a material which is much more able to resist deformation when under load. In contrast, expanded foams rely on the strength of the basic polymer, the type of cell predominating within the structure (open, closed or reticualted) and to some extent on the cell size.

It should be noted here that a comparison of foams of different densities is not strictly valid. In increasing the density of the foam, the structure of the material changes - for example the size of the bubble may change. Because the properties of foam are dependent on many contributing factors, we should be aware that density change alone may not be the cause of the change in strength. As with wood, foams owe their characteristics to a fairly complex combination of attributes and this should not be overlooked if a clear picture of foam performance is to be obtained.

The importance of rigid foams is based on their ability to insulate - from heat, sound and vibration - and on their ability to absorb energy on impact - their cushioning properties. However, modern practice has extended usage of foams as structural, load-bearing materials, leading to increased interest in mechanical properties. It is possible that certain types of foamed plastic could take over the role of wood in some applications, particularly if a cheap material were to become available which could be manufactured on site for use when needed and moulded to a required shape and size. It is interesting to note, however, that LPG container ships are still lined with balsa wood as an insulater - on the grounds of lower cost and higher strength to weight ratio.

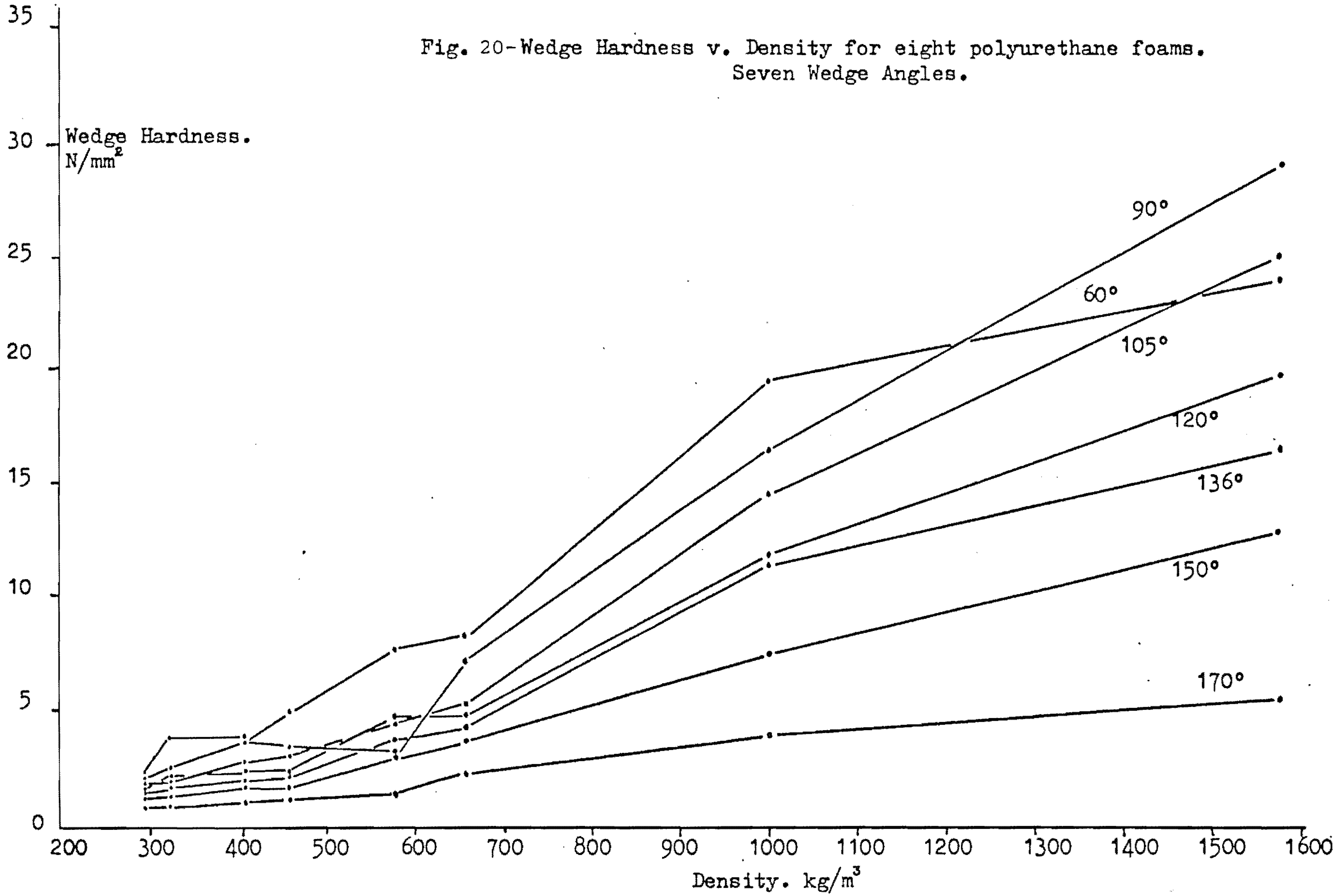


Fig. 20-Wedge Hardness v. Density for eight polyurethane foams.
Seven Wedge Angles.

4.4. THE EFFECT OF SAMPLE ORIENTATION ON WEDGE HARDNESS

As with all other tests methods, the test surface must be specified when referring to hardness and the results of wedge tests indicate a similar situation exists.

In the standard tests, such as the Janka method specified by ASTM D143-52 (1978), it is usual to measure both the end hardness - indentation parallel to the grain - and side hardness - perpendicular to the grain. The French Monnin test suggests testing on one face only, in this case, the radial face. Indenting on the tangential face is not recommended on the grounds that layers of tissue of widely different density will be encountered progressively as the tool penetrates the wood. This will be especially true with softwoods with their widely differing densities of earlywood and latewood. Douglas fir is an extreme case where earlywood and latewood densities can differ by a factor of four or so (Harris and Orman, 1958). The French also rejected end-hardness testing as it was considered to be simply a non-uniform axial/longitudinal compression test.

Tests were carried out using four selected timbers and indenting on all three surfaces using a Janka ball and a 136^{o} wedge. The results are compared in Table 8.

In general, tangential and radial hardness values are roughly similar for each of the species tested, but end hardness is considerably higher. Referring again to the analogy of wood as resembling a bundle of drinking straws - of rather squarish cross-section - glued together, and where a wide range of density, from balsa to Southern rata, is simply a result of variations in cell wall thickness.

It is useful to consider first transverse and longitudinal compression of wood before going on to examine hardness. With transverse compression the cylindrical fibres are readily squashed into elliptical tubes whereas in longitudinal compression the fibres must fail by some form of buckling. In fact the compressive strength parallel to the wood is small compared to the tensile strength, unlike metals. This is because the adhesion between cells is low (ca. 10^7 N/m^2 shear strength) and under compression a cell is able to buckle individually rather than as a coherent assembly: collapse is due to the weakness in transverse shear of the cell wall. In turn adjacent cells become overstrained by the failure of the individual cell and the "*crease*" propagators across the specimen. With thick-walled fibres of hardwoods and the tracheids of the denser softwoods, incipient failure is due to bending of individual fibres rather than by buckling. Occasionally as the "*crease*" develops the wood can break down into groups of fibres separated by longitudinal cracking. With an indenter on a transverse surface of the wood, a bending stress is superimposed on the uniaxial crushing force that causes collapse under tension. This longitudinal stretching - and failure - of the fibres is much greater under the Janka, which penetrates the wood deeply, than for the 136° wedge. Splitting across the grain can also occur with the Janka tool. The non-uniform loadings on the end surface, using these same tools, superimpose crushing and splitting modes of failure on the uniaxial compression. With a solid isotropic material, longitudinal and transverse compressive strengths would be the same, as would the respective hardness values. Thus, as a broad generalisation, the ratio of side hardness to end hardness tends to diminish as wood density increases.

Such a simplified model for wood as postulated above is not readily amenable to mathematical analysis. Furthermore, other factors have not been considered. The presence of specialised cells such as ray tissue and normal "imperfections" in the cell walls, particularly pits, presents a less simplified structure than that given above. The most notable effect of this is small difference in hardness detected when loading in orthogonal directions (radial and tangential) perpendicular to the grain. This is further exaggerated, especially in softwoods, by the tendency of growing wood to lay down its cells in alternating thin walled and thick walled rows. These earlywood and latewood bands have distinctly different strength properties and will present a series of soft then hard layers to an indenter loading on the tangential surface. It is for this reason that the Monnin test for hardness is not carried out on the tangential surface.

The results of tests on selected woods on three surfaces using a Janka ball and a 136^{O} wedge are shown in Table 8.

For the hardwoods, balsa and beech, tangential side hardness is slightly higher than radial hardness and end hardness is considerably higher than either of the side hardness values. The end hardness to side hardness ratio for the wedge (balsa 6.12, beech 2.93) is much higher than a similar ratio for the Janka hardness values (balsa 1.94, beech 1.23). A significant amount of failure occurs before the full penetration of the Janka tool is achieved and this is particularly noticeable on endgrain tests where woods have a tendency to split even when restrained. It is likely that this causes the low end/side hardness ratio for Janka tests. The end hardness to side hardness ratio for wedge indentations is again higher than a similar ratio for Janka hardness on the softwoods. Kahikatea shows a ratio of 3.48 for the wedge and 1.54 for the Janka test, Douglas fir shows a ratio of 1.85 for the wedge and 1.22 for the Janka test. An interesting trend is noticeable in that the end/side hardness ratio decreases with increasing density for both types of test, though absolute values of hardness do not appear to be closely related to density for end hardness determined by the wedge method. It may be unwise to infer too much from this aspect of the results as only four species do not give a good representation of the possible structural and density variations. The overall impression is one of hardness being affected by rigidity of the structure in the direction parallel to the grain, this being more important in low density timbers, whereas the actual physical bulk and its associated strength characteristics add significantly to the side hardness as the density of wood increases. The low result for endgrain wedge hardness of Douglas fir does not fit in readily with this explanation as Douglas fir has a high stiffness. Two possible explanations here might be the effect of splitting as a result of the stiff and unyielding fibres separating before bending occurs, or alternatively spiral (helical) thickenings of the fibres may increase crushing strength in the direction perpendicular to the grain. However, as the trend is not evident in the Janka results, the effect remains somewhat inexplicable.

	Janka Hardness		Ratio End/Side	136° Wedge Hardness		Ratio End/Side
Balsa ($141\ kg/m^3$)						
radial	1.6	(6.2)		1.67	(0.5)	
tangential	2.0	(10.0)		1.84	(1.8)	
endgrain	3.5	(8.5)	2.93	10.74	(6.3)	6.12
Kahikatea ($476\ kg/m^3$)						
radial	32.0	(5.3)		10.62	(0.9)	
tangential	39.7	(4.2)		11.41	(19.0)	
endgrain	55.2	(5.1)	1.54	38.37	(6.8)	3.48
Hard beech ($608\ kg/m^3$)						
radial	62.9	(3.2)		23.11	(6.4)	
tangential	65.7	(3.5)		27.84	(5.8)	
endgrain	79.0	(1.3)	1.23	74.70	(4.1)	1.94
Douglas fir ($628\ kg/m^3$)						
radial	68.4	(6.9)		26.63	(10.8)	
tangential	69.3	(6.0)		29.40	(8.5)	
endgrain	83.9	(19.4)	1.22	54.68	(3.2)	1.85

Table 8 - Janka and 136° wedge tests on three faces of four representative timbers. Figures in N/mm^2, coefficients of variability in brackets (%). 12% moisture content.

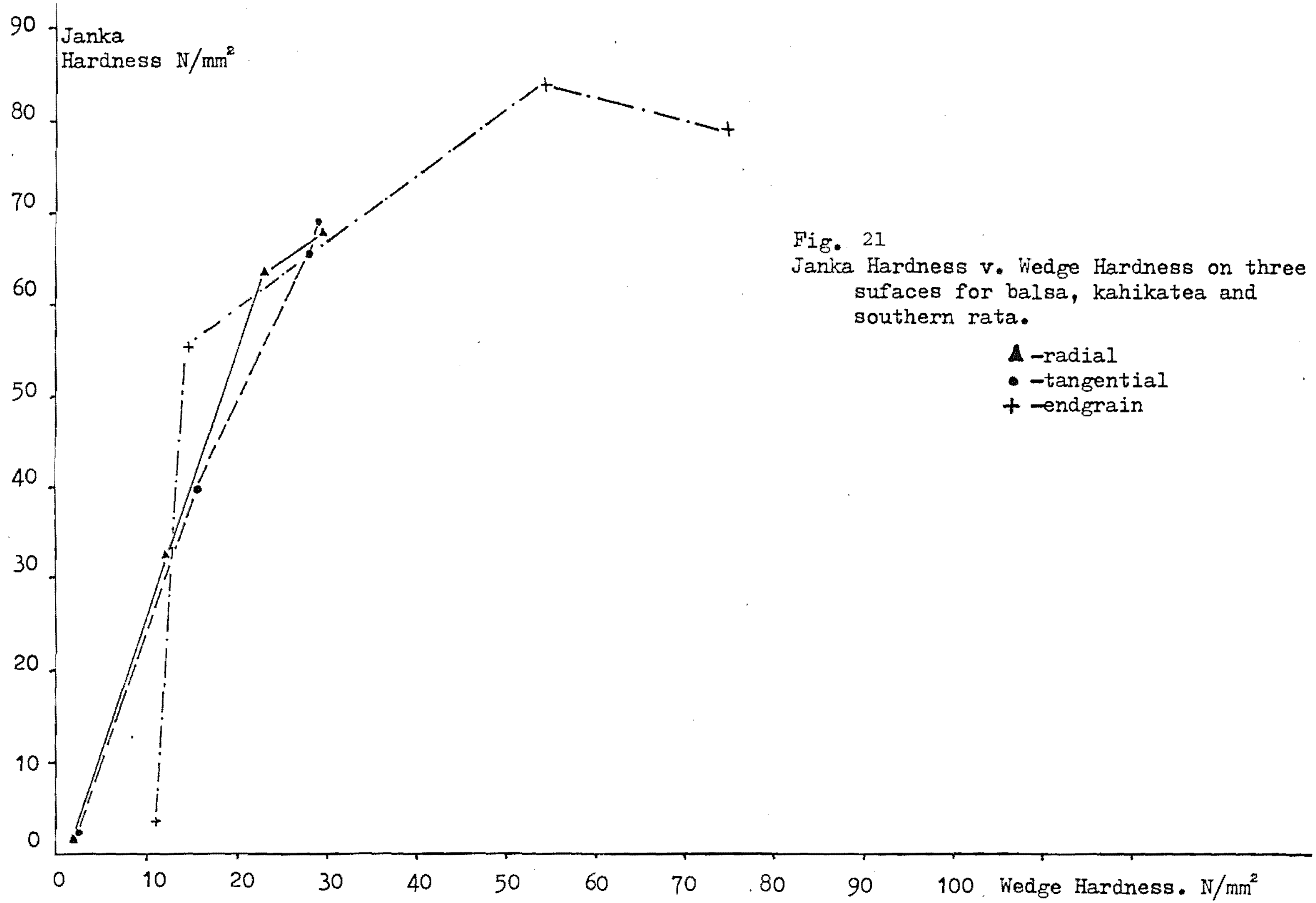


Fig. 21
Janka Hardness v. Wedge Hardness on three sufaces for balsa, kahikatea and southern rata.

4.5. INDENTATION OF WOOD USING CYLINDRICAL AND SPHERICAL TOOLS

Three Monnin type cylindrical indenters of diameters 10mm, 30mm and 50mm, and three spherical indenters of diameters 11.28mm (Janka ball), 30mm and 50mm, were used to study the effect of tool size on hardness. Tests were carried out on three timbers representing low (balsa), medium (kahikatea) and high (southern rata) density. All the indentations were made at a cross-head speed of 0.5mm/min. under conditions of 20^{o}C and 55% relative humidity and on the radial surface of each timber.

The size of the 50mm tool precludes indenting to a depth of half the diameter as prescribed in the standard Janka tests. Two alternatives are available: indentation to an arbitrarily chosen but convenient depth or to different depths for each tool to give impressions of geometric similarity. With the continuous recording apparatus available, it is possible to obtain hardness values for both these situations from the same test and results are shown in Table 9.

The Janka type tests show hardness values at a penetration depth of $^{1}/\pi$ mm for each indenter and hardness values taken at penetration depths computed to give geometric similarity. As would be expected, the hardness value recorded at $^{1}/\pi$ mm depth increases as diameter of the tool increases. At the penetration depth computed to give geometrically similar impressions, the hardness values show very loose agreement within each species. The diameter of the largest sphere (50mm) dictated the maximum depth of impression allowable without reaching the edges of the sample. Although the sample was restrained, it was not possible to ensure that the restraining wood was set at exactly the same height as the test sample so that any slight difference in height at the sample/restrainer interface could significantly affect results. For the 50mm indenter, the indentation depth was set at 0.75mm which required the 30mm and 11.28mm indenter to penetrate to depths of 0.45 and 0.17mm respectively. A comparatively high degree of variability was encountered, particularly for the standard Janka tool (diameter = 11.28mm). Considering the enormous amounts of variability normally encountered in wood, the results show a reasonable agreement for hardness within each species. When working at very low depths of indentation some uncertainty regarding the lift-off point of the load/penetration curve introduces a relatively large error into results. To avoid this, higher penetration depths could be used thus reducing the lift-off error as a percentage of the total depth value, but this in turn introduces complications arising from the complex failure patterns under deep penetration. Lift-off error is a problem with all the cylindrical and spherical indenters, but can easily be avoided with wedges if care is taken to level the sample. Even with the sample surface at an angle to the wedge indenter, it is a simple matter to account for this in analysis, as the relationship between load and area increase is linear.

Additionally, with the ball test, there is a tendancy for the rate of load increase to fall away as penetration increases and this occurs most rapidly with the less dense species. With balsa, the load increase with penetration levelled out smoothly, but starting early in the test, so that towards the end of the test with the smallest Janka tool the load was in fact decreasing with depth increase. Similar patterns were evident for kahikatea and southern rata except that the fall off begins much later and is in the form of intermittant drops in load - apparently due to some form of microfailure. For kahikatea, these drops were frequent and fairly small, whereas for southern rata they tended to be less frequent and much larger. A similar indication of microfailure occurred in some of the wedge tests with sharp angle wedges and was mentioned in an earlier section. The most likely cause of this type of failure is tensile failure of the bending surface fibres. After removal of the indenter, surface checking is evident indicating that fibres did indeed fail in tension. However, it is unlikely that the deformation is so simple and other factors such as cell wall crushing will certainly be involved. A less severe form of this load checking had been noted with wedge indentations, but was found to be significant only with angles below 120 degrees. This would indicate that it is related to conditions involving high strains where chain slipping progresses irregularly to relieve the build up of stress.

The hardness values in the Monnin type tests were calculated for specific indentation depths, such that the angle subtended at the point of intersection of the two tangents to the cylindrical tool - the tangents touching the cylinder at the wood air interface - was identical to a chosen wedge angle. (See Fig. 22).

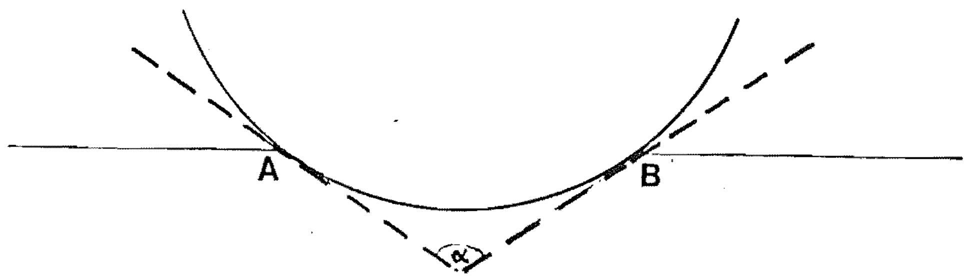


Fig. 22 Monnin indentation showing tangents and wedge equivalent.

It was impossible to indent the larger tools to sufficient depth to give a comparison for all wedge angles and all the available data is presented in Table 10.

The small indenter, designated Monnin A, shows hardness values, in N/mm^2, which are roughly similar to the values for wedges of corresponding angles. It would be expected that, since strains are lower for cylinders than for wedges of corresponding angle, that hardness values would be lower. This does not appear to be the case, except for southern rata. Kahikatea shows an irregular response to loading with the small Monnin tool, hardness rising very rapidly as indentation proceeds. It is also evident that the variability of results when testing with the small Monnin tool is extremely high and is generally much higher than with the wedge. The results are reasonably consistent with expectation, considering again the possible sources of variation which were identified for the spherical indenters.

The larger Monnin type tools - Monnin B, diameter 30mm and Monnin C, diameter 50mm - show a very similar response and results are in keeping with the smallest cylindrical tool. However, both large tools show results with much less variability than the 10mm tool which supports the findings of Campredon and Gauthier (1943) who report similar tests using different size cylinders.

The results suggest that, in terms of consistency of results, the wedge test is the most reliable. It is notable that, for the Jankas and Monnins within one individual test group (i.e. one tool on one species) variability is different if hardness results are computed for differing penetration depths. This indicates that the load/time response is not the same for each test, unlike the wedges where hardness remained constant regardless of depth, and variability was similar within any group at any depth of indentation. For example, the 136° wedge shows variability of hardness at a depth of 0.17mm to be 4.4% for kahikatea. At $^{1}/\pi$ mm depth this was 5.9% and at 1kN load (as in Table 10) 5.6%. In contrast, the figures for kahikatea indented by Janka A are 14.1% at 0.17mm, 4.1% at $^{1}/\pi$ mm. The Monnin A results show variability ranging from 39.6% to 11.2% depending again on penetration depth.

Species	Janka A diameter 11.28mm		Janka B diameter 30mm		Janka C diameter 50mm	
1. Indentation Depth = $1/\pi$ mm						
balsa	1.82	(0.0)	2.23	(1.3)	3.35	(16.2)
kahikatea	15.96	(4.1)	16.34	(5.8)	21.88	(5.2)
southern rata	54.22	(9.9)	65.26	(19.8)	71.53	(21.3)
2. For geometric similarity						
indentation depth	0.17mm		0.45mm		0.75mm	
balsa	1.26	(28.0)	0.52	(3.2)	0.98	(15.4)
kahikatea	8.40	(14.1)	4.16	(5.9)	6.84	(5.0)
southern rata	23.52	(22.4)	18.06	(14.0)	25.48	(6.2)

Table 9 - Janka hardness (N/mm^2) for indenters of different sizes and at different penetration depths. Figures in brackets are coefficients of variation (%).

	Monnin A diameter 10mm		Monnin B diameter 30mm		Monnin C diameter 50mm		Wedge	
Balsa								
170	0.669	(43.3)	0.59	(20.3)	0.67	(23.9)	0.34	(16.0)
160	0.689	(36.2)	0.83	(28.9)	1.94	(23.7)	0.57	(9.7)
150	0.993	(26.2)	1.29	(21.7)	2.49	(16.7)	0.78	(8.5)
136	1.641	(11.0)	2.12	(5.7)	-		1.16	(4.3)
120	2.359	(8.1)	2.72	(1.1)	-		1.43	(3.6)
105	2.952	(4.7)	-		-		1.45	(2.5)
90	3.379	(4.14)	-		-		2.03	(3.1)
Kahikatea								
170	4.97	(39.6)	8.24	(25.0)	11.9	(26.1)	6.84	(2.9)
160	13.33	(45.4)	17.44	(18.0)	-		8.59	(8.5)
150	21.28	(28.2)	22.90	(10.6)	-		10.65	(0.6)
136	26.75	(14.6)	26.62	(6.7)	-		13.68	(5.6)
120	29.60	(12.4)	29.47	(8.4)	-		19.29	(4.0)
105	32.04	(11.2)	-		-		24.27	(11.6)
90	-		-		-		23.32	(15.6)
Southern rata								
170	13.88	(22.5)	18.61	(34.0)	17.83	(17.2)	20.26	(11.0)
160	32.39	(19.1)	32.85	(18.6)	47.73	(11.3)	32.81	(6.2)
150	48.56	(23.1)	51.72	(11.6)	65.35	(7.6)	45.36	(4.9)
136	66.72	(6.4)	80.83	(15.1)	-		72.92	(1.8)
120	85.47	(5.7)	88.85	(4.7)	-		75.23	(8.1)
105	102.99	(4.7)	-		-		118.00	(1.6)
90	119.50	(22.5)	-		-		122.64	(8.3)

Table 10 - Hardness of Balsa, Kahikatea and Southern rata for the three Monnin type tools. Hardness values shown for corresponding wedge angles. Moisture content 12%. Figures for hardness in N/mm^2. Figures in brackets are coefficients of variation. (%).

Section C

5. THE WEDGE HARDNESS OF TIMBERS AND THE RELATIONSHIP BETWEEN WEDGE HARDNESS AND OTHER STRENGTH PROPERTIES.

Twenty species of timber were chosen so that a large density range was covered. Their common names, listed below, are used throughout the text. Full botanical names are given on Page 248. The figures presented in brackets are density values based on measurements of air dry (approximately 12%) volume and oven dry weight, kg/m^3.

Balsa	(141)	Hard beech	(608)
P. *strobus*	(303)	Douglas fir	(628)
Douglas fir	(418)	Hinau	(633)
Pukatea	(441)	European beech	(636)
Kahikatea	(478)	Pohutukawa	(674)
Kauri	(491)	Northern rata	(697)
Tawa	(524)	Mapou	(746)
Scots pine	(526)	Puriri	(813)
Mangeao	(553)	Southern rata	(1000)
Rewarewa	(598)	Southern rata	(1274)

Apart from European beech and Scots pine, imported from the U.K., the two Douglas firs from the U.S. and the balsa of uncertain origin via the U.K., all the timbers are New Zealand grown. Of these, only P. *strobus* is not indigenous to New Zealand. Inclusion of overseas species helped to increase the density range and also allows a certain amount of cross reference with other work.

5.1. EXPERIMENTAL PROCEDURE

The wood was machined carefully to produce sticks with three orthogonal faces in the radial, tangential and longitudinal directions respectively. These could not, of course, be perfect in every case because of minor grain defects. In cases where samples were seen to have defects, the sample was discarded without investigation. Only small clear specimens were used in the testing.

The sticks were machined as accurately as possible to produce 2x2x30cm test samples. These were then randomly allocated to two separate groups of approximately equal size - about 200 samples in each. One batch remained in the conditioning room, where all the timber had been stored for three months, under controlled conditions of $20^{o}C$ and 55% relative humidity corresponding to approximately 12% moisture content for most woods. The second batch was subjected to a prolonged vacuum-water soak cycle for 48 hours and then stored in water for several weeks prior to testing. Captaphol was added to the water to prevent decay.

Testing of the samples was based on the recommendations of British standard BS 373 (1957) - Testing of small clear specimens of timber. Tests carried out were to determine shear strength parallel to the grain, cleavage strength parallel to the grain, compressive strength parallel and perpendicular to the grain, modulus of elasticity in static bending, modulus of rupture in static bending, the Janka hardness test and the wedge hardness test using eight different wedge angles. All the hardness tests were based on Meyer Hardness, i.e. load divided by projected area.

An Instron test machine, model 1195, was used for all the tests, offering sophisticated control of tests and continuous readout on a chart recorder.

For each test and with each species there were three replicates, making 42 tests for one species in the air dry state, 840 tests for all the samples in the air dry state.

In order to obtain an indication of the effect of moisture content a further 620 tests were carried out on the green timber. The results are summarised in Tables 28 and 29 (Appendix G).

5.2. ANALYSIS OF DATA - GENERAL

The data obtained was divided into two groups for analysis. The hardness values obtained from the wedge tests, for eight included angles, were defined as the dependent (y) variables. The results of the remaining tests become the independent (x) variables and correllations are to be sought for all combinations of independent (y) and dependent (x) variables.

A stepwise multiple regression package was used to fit the data to the following model:

$$y = \gamma_0 + \gamma_1 x + \gamma_2 x^2 \qquad \gamma_0, \gamma_1, \gamma_2 \text{ are constants}$$

In the first step, the model is considered in which $\gamma_2 = 0$ so that the relationship between x and y is linear. In the next step, the assumption is that $\gamma_2 \neq 0$, and a quadratic function is included in the relationship. The linear regression equations are recorded in Tables 11 to 24.

In cases where the inclusion of the quadratic term improves the regression coefficient (R^2) more than a marginal amount then the equation including this term is listed. The quadratic term in fact improved the fit of the data to the model in almost every case. The data points are plotted in the graphs, Fig. 23 to Fig. 32, and the linear regression line is included in all cases unless the linear relationship is very poor ($R^2 < 0.5$). The presence of the straight line on the graphs is not an indication that this is a true relationship - it must be borne in mind that a straight line relationship can be obtained for almost any set of data in the type of stepwise regression package used here. However, in many cases, the linear equation describes reasonably well the relationships under consideration. The desirability of accepting such a model is discussed for individual cases in the following section.

5.3. THE CORRELATIONS

In total, 29 correlations were looked at, of which 15 involved the eight wedge angles, 60^{o}, 90^{o}, 105^{o}, 120^{o}, 136^{o}, 150^{o}, 160^{o} and 170^{o}. Nine characteristics of wood other than wedge hardness were included and both green and air dry wood was considered. In total, this amounted to 221 relationships (Tables 11 to 38).

5.3.1 THE RELATIONSHIP BETWEEN WEDGE HARDNESS AND DENSITY

The relationship between hardness, as measured by presently accepted standard methods, and density has been considered in an earlier section. As was pointed out then, density probably has a greater effect on hardness than any other characteristic of wood. It's influence on strength properties is well documented and density is, justifiably, regarded as a good guide to the performance of wood under a given set of conditions. For this reason, the relationship between Wedge Hardness and density has been given the most rigorous analysis.

Regression equations, based on the model suggested in Section 5.2, are determined for the unadjusted density with Wedge Hardness and are given in Table 11. The actual values are plotted in Fig. 23 (a) to (h).

Inclusion of different species in the density range means that the woods tested may have their densities modified by differing amounts of extractives. This was taken into account by adjusting the density on the basis of percentage by weight of extractives contained in representative samples of each species. Twenty samples of wood flour were obtained and extractive content determined using the methods of ASTM D1105-56, Preparation of Extractive Free Wood, - Alcohol-benzene extraction, and ASTM D1105-56, Preparation of Extractive Free Wood,- Water Extraction.

Adjusted densities are listed in the summary table (Appendix G) alongside unadjusted densities.

Regression equations for the adjusted density/Wedge Hardness relationship are also determined and are given in Table 11. Actual points are plotted in Fig. 24 (a) to (h).

It is immediately apparent from the tables and graphs that the correlation coefficients for the adjusted density are slightly better than those for unadjusted density. The data also suggests that the quadratic model describes the relationship better than the linear model, which is in keeping with previous work relating hardness to density. The best linear fit is with the 105° and 136° indenters. The best quadratic fit is for the 60°, 105° and 136° indenters, indicating that there is no systematic difference in the correlation coefficients as the angle of the wedge changes. This is further supported by the analysis of variance on the data for adjusted density and Wedge Hardness in Appendix E.

The analysis is done in a stepwise manner and a description of the relationship is built up using the parameters

B_o - the intercept constant; [1]
RHO - density, kg/m^3;
ANGLE - in degrees;
RHOXAN - the interaction between angle and density
RHOSQ - square of density
ANSQ - square of angle.

The significance of each of these parameters depends to some extent on which of the others are also being included in the equation. For example, in step number 6 of Appendix E the effect of angle is relatively low, whereas in step 5, when square of angle is not included, it appears much more significant. Similarly, in step 2, where neither the interaction term nor the angle squared term is present, angle effect is high significant.

In summary, the data indicates the following; (see step 7, Appendix E).

(i) Wedge Hardness is affected by density and, as both the density term and the square of density term are significant, the relationship is probably based on density raised to a power between one and two.

(ii) The effect of angle change is present and is negative (i.e. hardness decreases with increasing angle), but the effect is highly influenced by changes in density, as shown by the significance of the interaction term.

1 - The mechanism of the package is such that B_o is a variable which is always considered as $B_o = 1$. As such, the coefficient of B_o is, strictly, the intercept constant, but will in any case be numerically equal to B_o. In the model in section (iii) $\gamma_1 = B_o$.

(iii) The angle squared term is significant and positive, which indicates that the decrease in hardness with angle increase becomes less marked as angle increases.

Inclusion of all the parameters in a model of the form

$$y = \gamma_1 + \gamma_2\rho + \gamma_3\rho^2 + \gamma_4\beta\rho + \gamma_5\beta + \gamma_6\beta^2$$

where ρ = density, β = angle, γ = constant

accounts of 95.9% of the variation, as can be seen in the summary table of Appendix E. If only the constant B_o is included with density (RHO), 69.9% of variability is accounted for. Including density squared (RHOSQ) improves this to 70.9%, but it must be remembered that this is in the presence of several other variables. In the regression equations, the variability due to angle is removed by considering each angle separately - thus the high regression coefficients (up to 94.1% for the 136^o angle) would be expected.

It now remains to identify and interpret the possible causes of the response of hardness to changes in other variables.

The increase in hardness with density is the most obvious response. It is to be expected that a less dense material will be less resistant to penetration by an indenter if we consider for a moment the sources of this resistance. Density in cellular materials is a consequence of the amount of void space within the matrix. Thus denser woods derive their resistance to any form of compression, including indentation, from the lack of void space available for deformed material to move into. It is also likely that their cell walls are thicker and stiffer than those of less dense woods and this also helps to present a more incompressible medium. In low density woods the rigidity of the cellular matrix is virtually all the material has to rely on for strength in compression.

The improved correlation with the density adjusted to account for extractive content is due to the bulking effect of these materials - little or no strength is imparted by the presence of the extractives in wood.

The effect of changing angle on hardness has to be considered along with the influence of density on the type of deformation caused. The positive interaction term (RHOXAN), indicates that, though hardness decreases with angle, the decrease becomes less evident if density is increased. Several factors are involved here which could contribute to the effect.

The fibres underneath an indentation made by, for example, a 90^{o} wedge will exceed the elastic limit more quickly than those under a 136^{o} wedge and more plastic deformation will occur. The fact that unloading curves for low angles are much steeper than those for high angles suggests that this is the case and the discussion in the section dealing with loading rate effects (P. 47), indicating the nature of the deforming mechanism is in agreement with this.

As angle increases the deformation becomes similar to simple compression. With increasing density the material becomes more incompressible and this effect is more marked than the increase in resistance to the cutting, cleavage, or tensile failure of bent surface fibres evident under indenters of low angle. It was noted with the foams that those of very high density with sharp wedges gave low hardness readings - again resistance to cutting, or at least resistance to plastic failure under very high strains, is not enhanced significantly by increasing density.

A number of workers have reported the relationship between hardness and density (see literature review). Many formulae have been suggested to describe this relationship, but the most commonly accepted is

$$H = \rho^n \qquad \text{where} \quad H = \text{Hardness}, \quad \rho = \text{density}, \quad n = \text{constant}$$

The value of n is quoted as being as low as 1·1 and as high as 2.25 in some cases. The actual value of n depends on many factors such as moisture content and, apparently, the source of the timbers used to determine the relationship. Trendelenburg (1933) and Ylinen (1943) comment on this. It would be unwise to formulate a relationship between any two of woods properties and expect anything more than a good indication of what could happen. It is thus likely that a number of mathematical models will, on inclusion of the pertinent coefficients, describe the relationships between the density of wood and its strength properties. It is evident from analysis of results in this report that a linear relationship explains the variation of hardness with density very well, especially if the density range is restricted to one commonly associated with timbers in general use, about 400 - 700kg/m^3. The use of a polynomial model improves the prediction outside this range, but in most cases this is not a large improvement. The use of a parabolic function of the form $H = \rho^n$ is justifiable as it explains results reasonably well. However, in this report, the linear regressions based empirical methods are extremely reliable. Introduction of a curvilinear relationship increases the 'fit' of the line to the data, but the indication is that improvement is small. The diagram (from Ylinen, 1943) on P. 27 shows how the linear and curvilinear relationships differ for American Hardwoods. The attraction of the equation used in this study, i.e. of the form

$$y = a + bx + cx^2$$

is that it is essentially linear for the low to moderate densities, deviating as density values increase.

Wedge angle (degrees)	Constant	Coefficient of x	Coefficient of x^2	R^2
Wedge Hardness, H_w, v. Unadjusted density (ρ). Air dry.				
60	-47.350	0.172	-	0.8537
90	-32.721	0.123	-	0.8633
105	-32.714	0.112	-	0.8869
120	-18.356	0.073	-	0.8740
136	-17.897	0.064	-	0.8676
150	-10.585	0.043	-	0.8682
160	-6.982	0.032	-	0.8613
170	-2.656	0.018	-	0.8412
60	1.323	0.0147	0.00011	0.9155
90	-10.586	0.0489	0.0005	0.8879
105	-5.253	0.0229	0.00006	0.9322
120	-6.586	0.0347	0.00003	0.8933
136	0.126	0.0055	0.00004	0.9260
150	-4.175	0.0226	0.00001	0.8842
160	-4.413	0.0238	0.00001	0.8660
170	-2.785	0.0184	0.00000	0.8412
Wedge Hardness, H_w v. Adjusted density (ρ). Air dry.				
60	-48.138	0.1880	-	0.8721
90	-32.982	0.1310	-	0.8741
105	-32.848	0.1216	-	0.8966
120	-18.319	0.0789	-	0.8785
136	-18.288	0.0701	-	0.8913
150	-10.569	0.0471	-	0.8731
160	-6.821	0.0345	-	0.8530
170	-2.593	0.0194	-	0.8378
60	-3.310	0.0334	0.00012	0.9204
90	-13.769	0.0649	0.00005	0.8924
105	-7.895	0.0355	0.00006	0.9334
120	-8.136	0.0438	0.00003	0.8928
136	-1.545	0.0122	0.00004	0.9410
150	-5.143	0.0284	0.00001	0.8844
160	-4.988	0.0282	0.00000	0.8553
170	-3.229	0.0216	0.00000	0.8387

Table 11

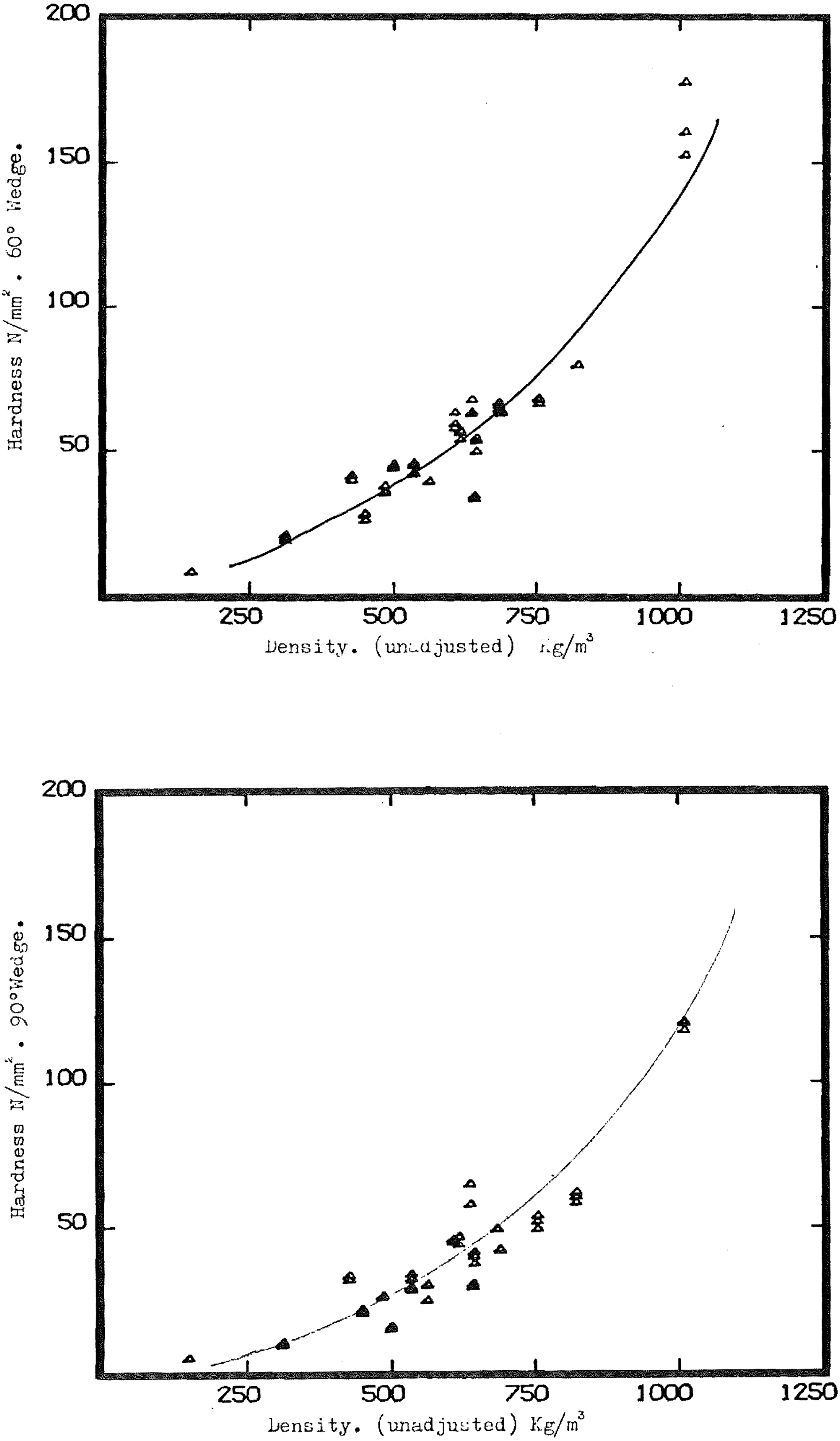
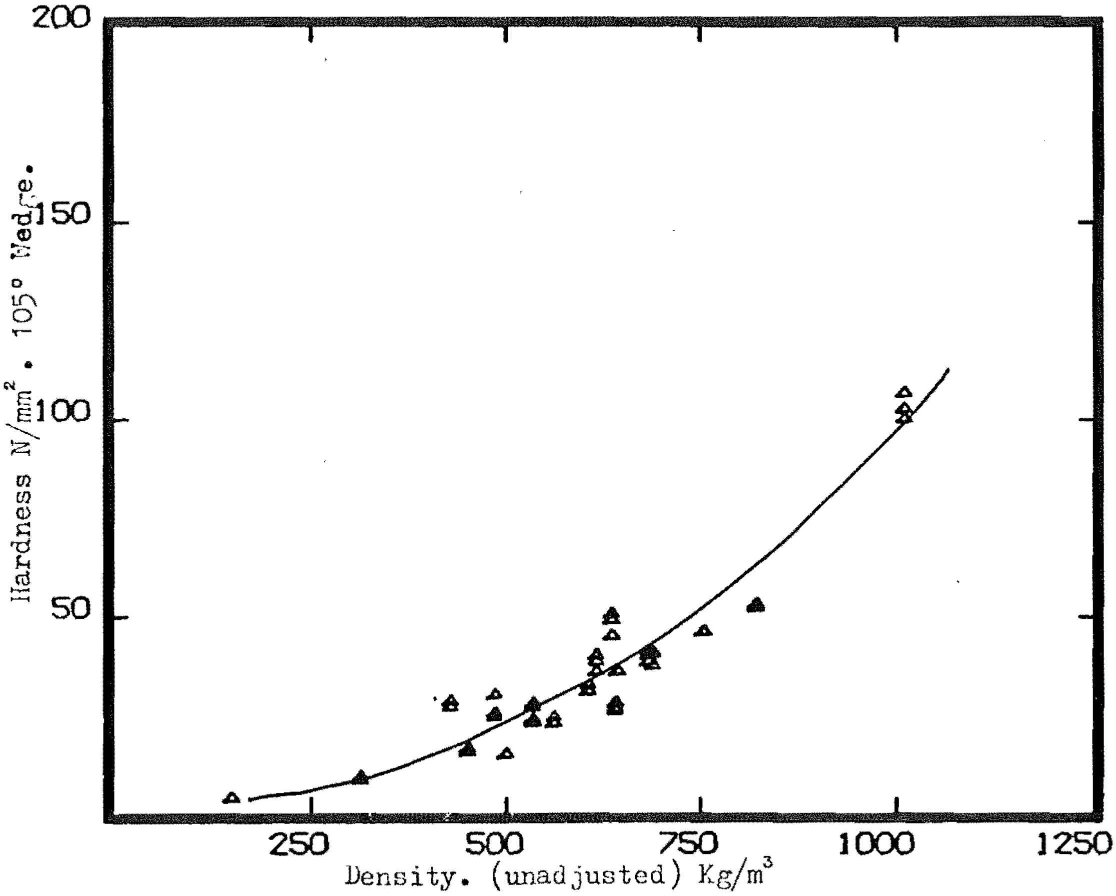


Fig. 23 - (a) and (b) Wedge Hardness versus Unadjusted Density. 12% Moisture Content.



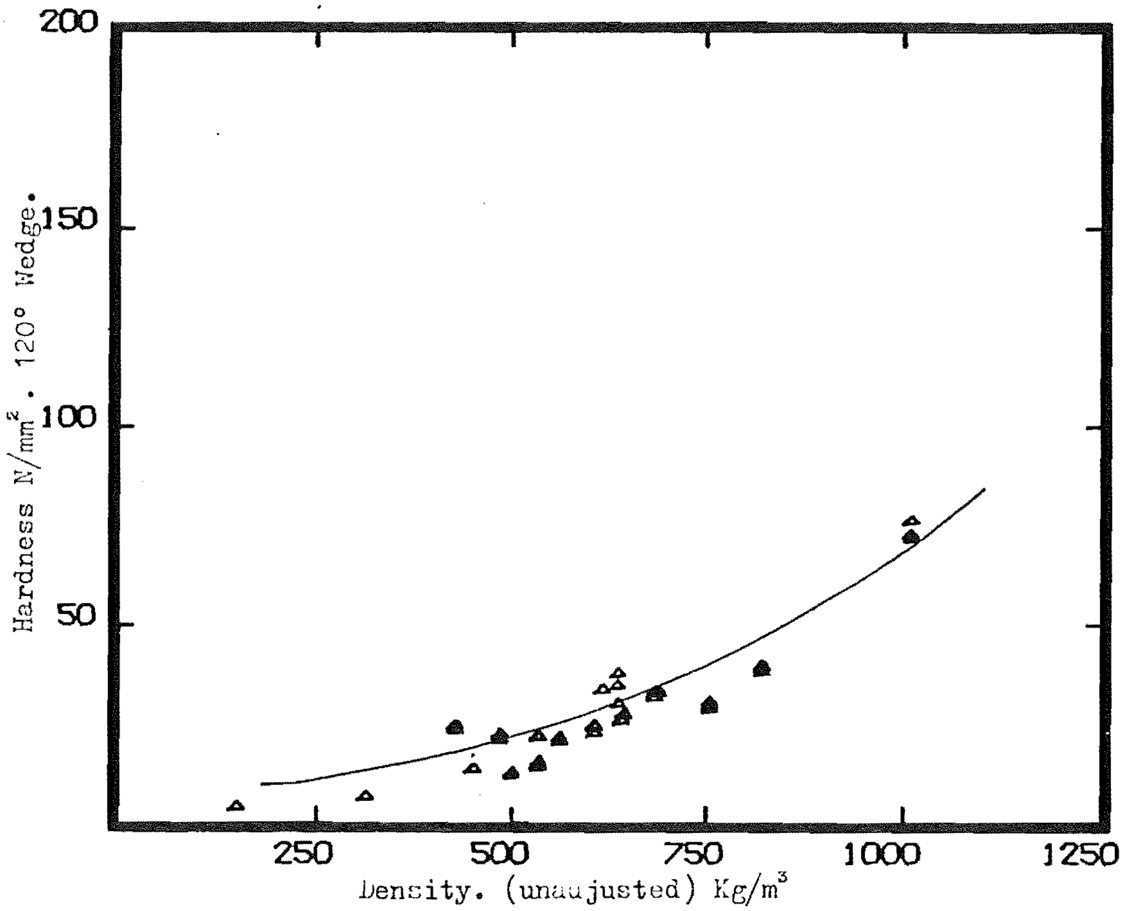
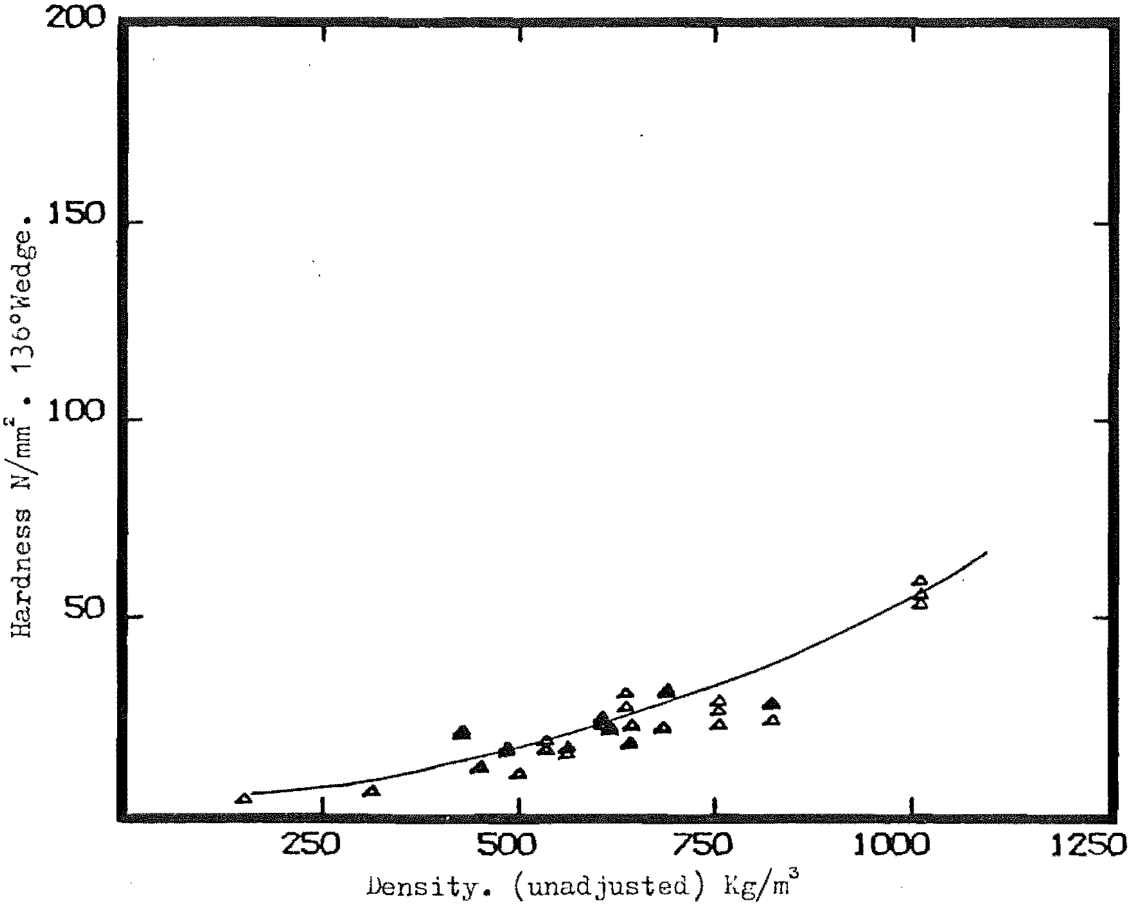


Fig. 23 - (c) and (d) Wedge Hardness versus Unadjusted Density. 12% Moisture Content.



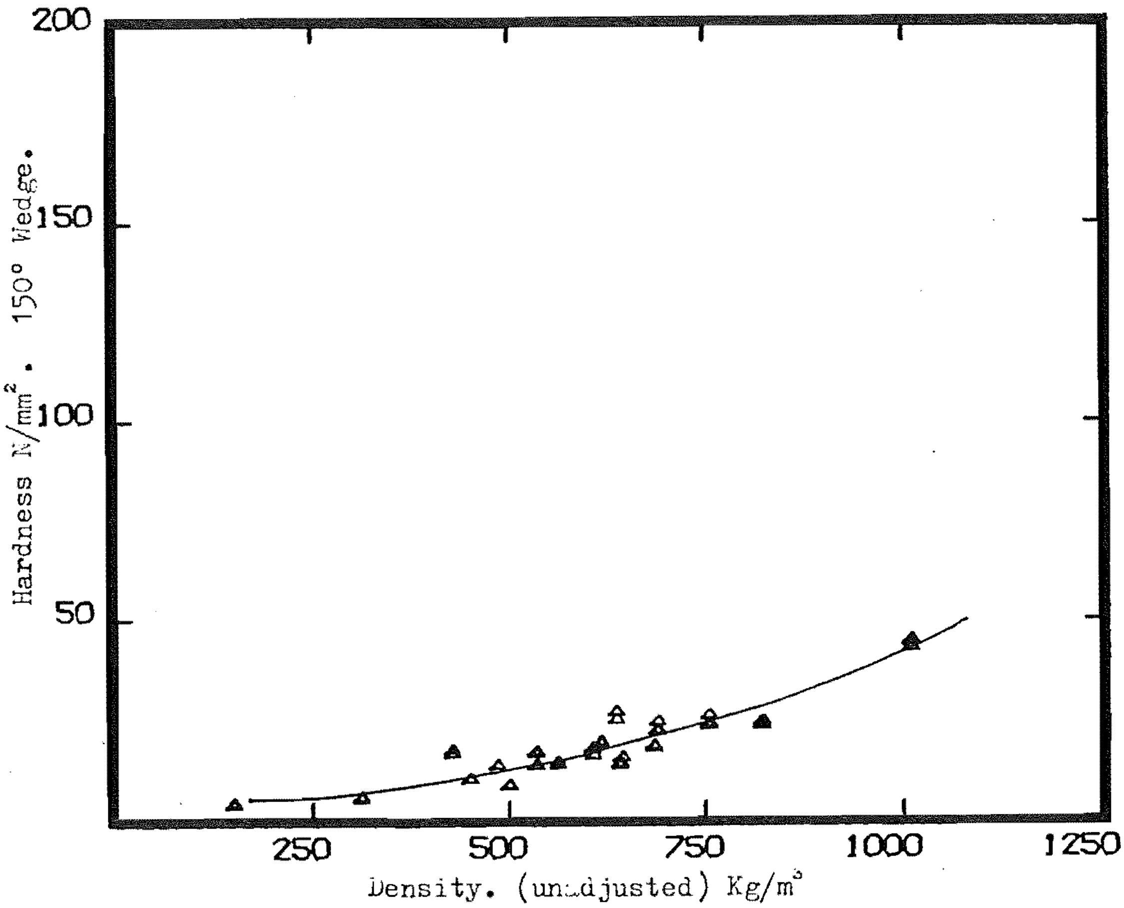


Fig. 23 - (e) and (f) Wedge Hardness versus Unadjusted Density. 12% Moisture Content.

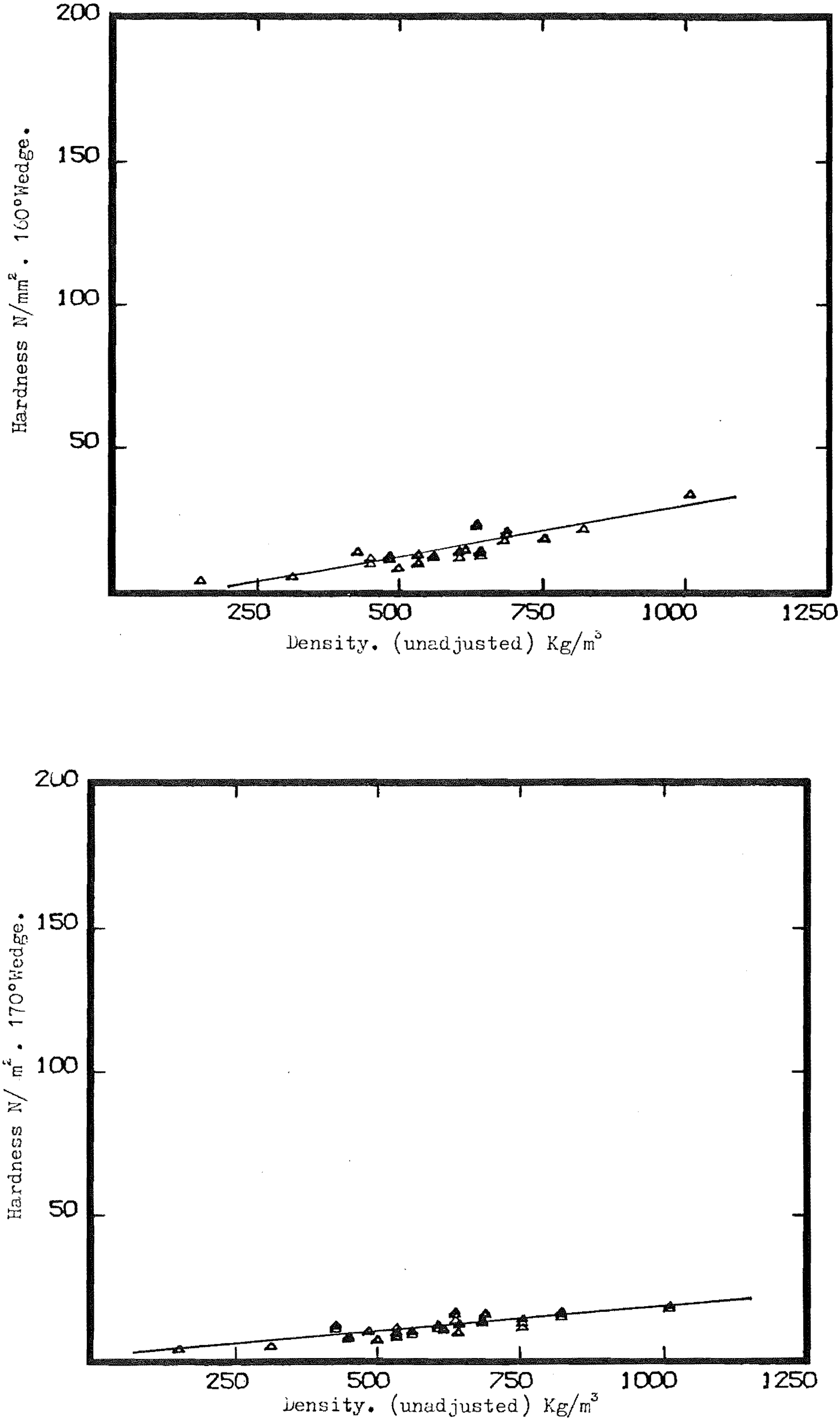
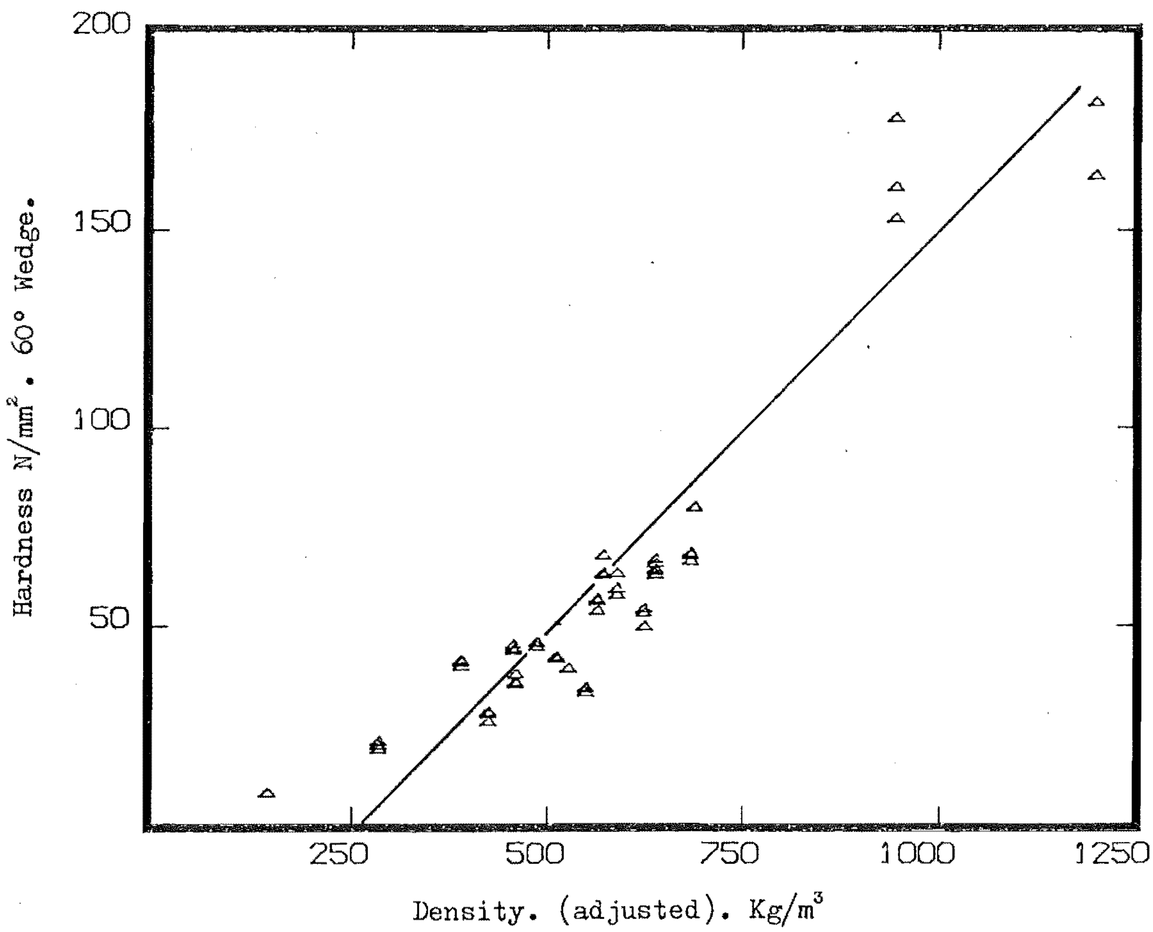


Fig. 23 - (g) and (h) Wedge Hardness versus Unadjusted Density. 12% Moisture Content.



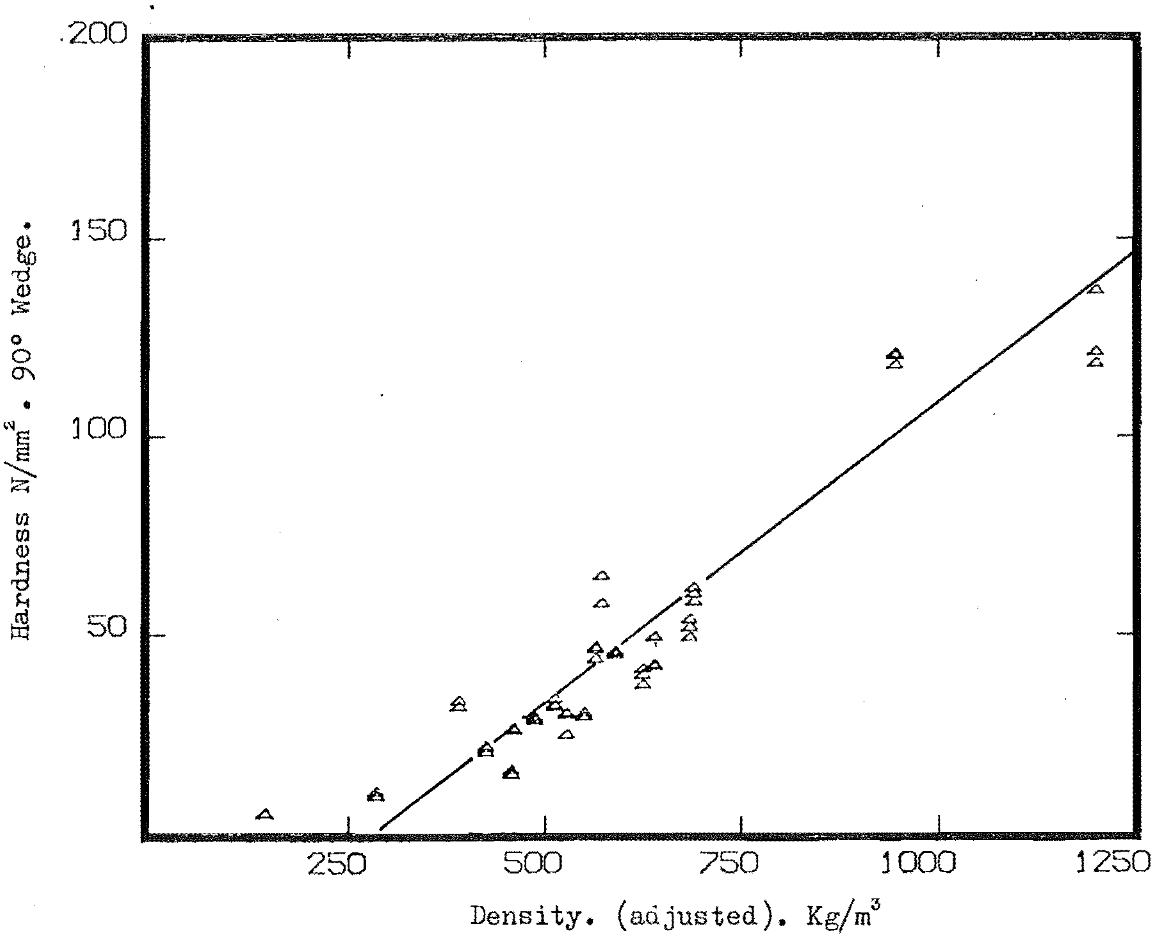
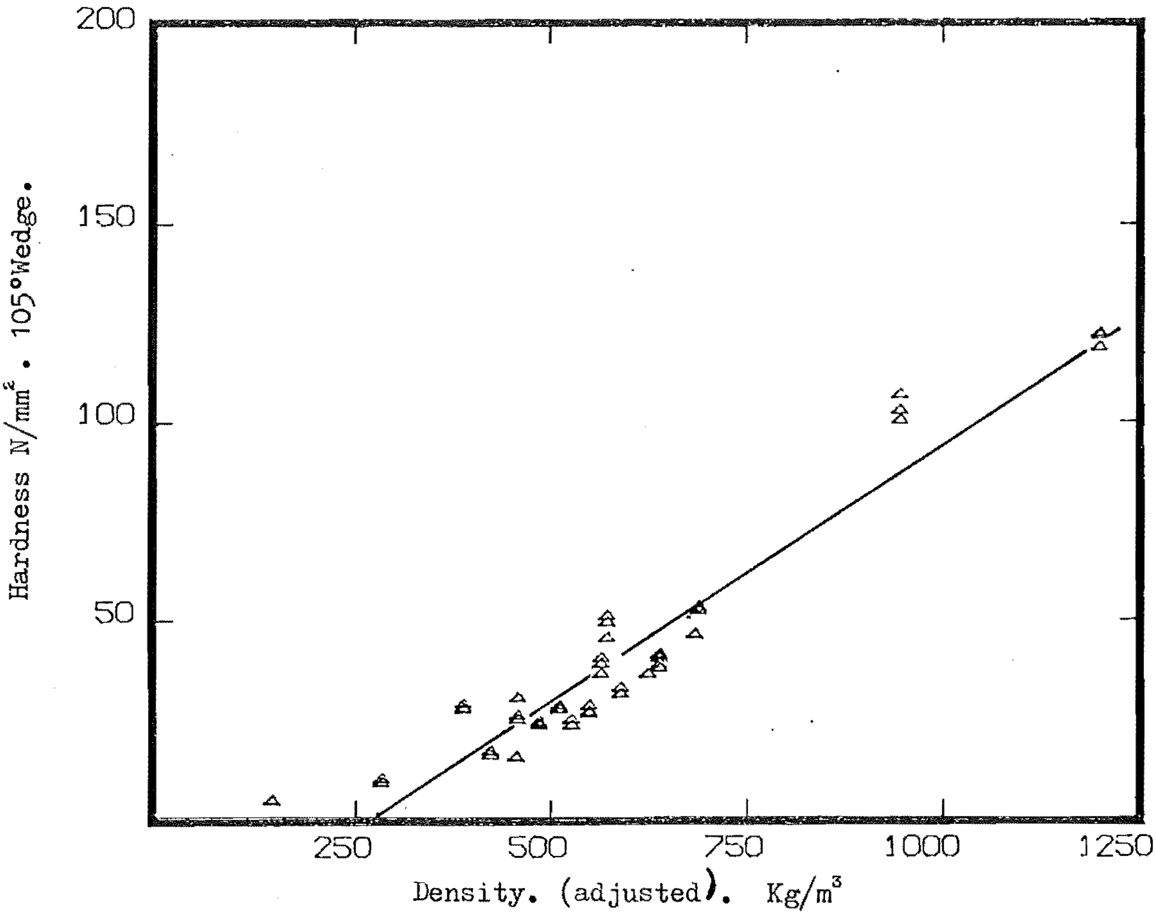


Fig. 24 - (a) and (b) Wedge Hardness versus Adjusted Density.
12% Moisture Content.



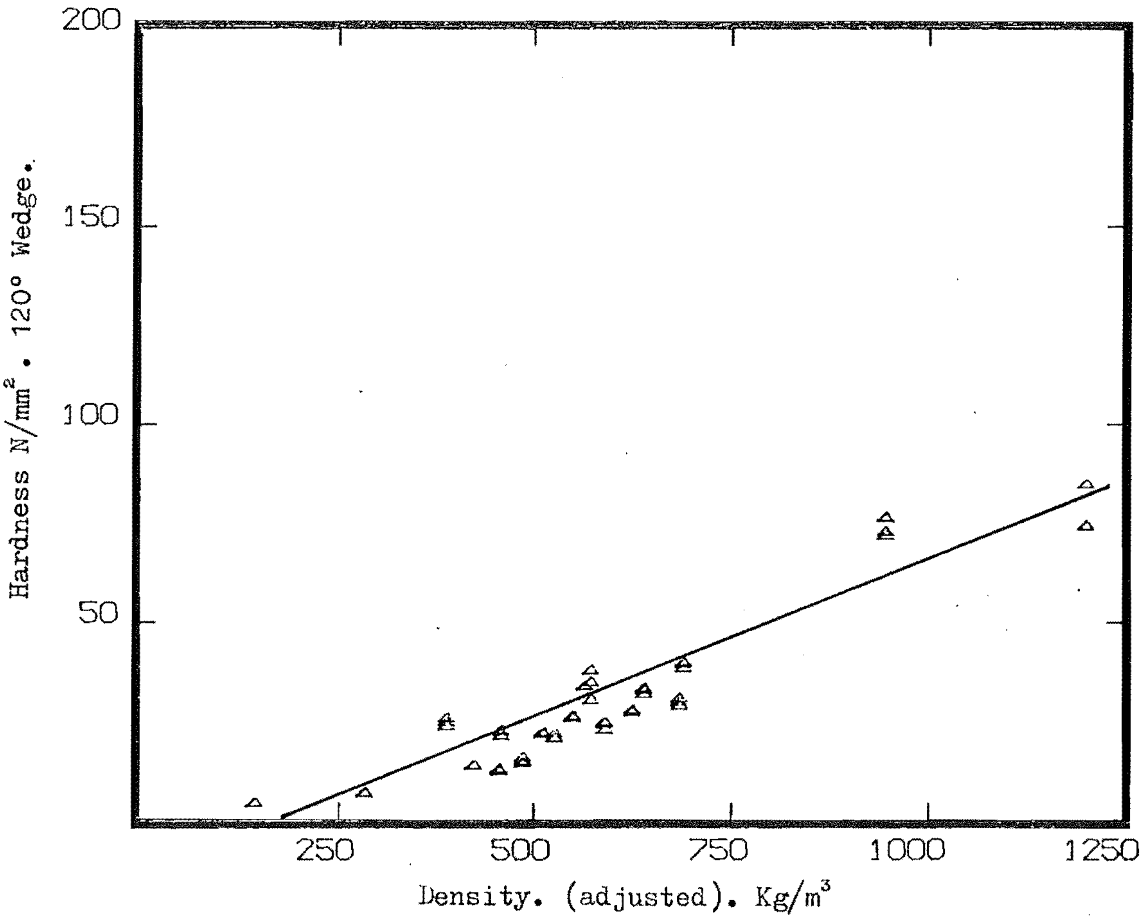
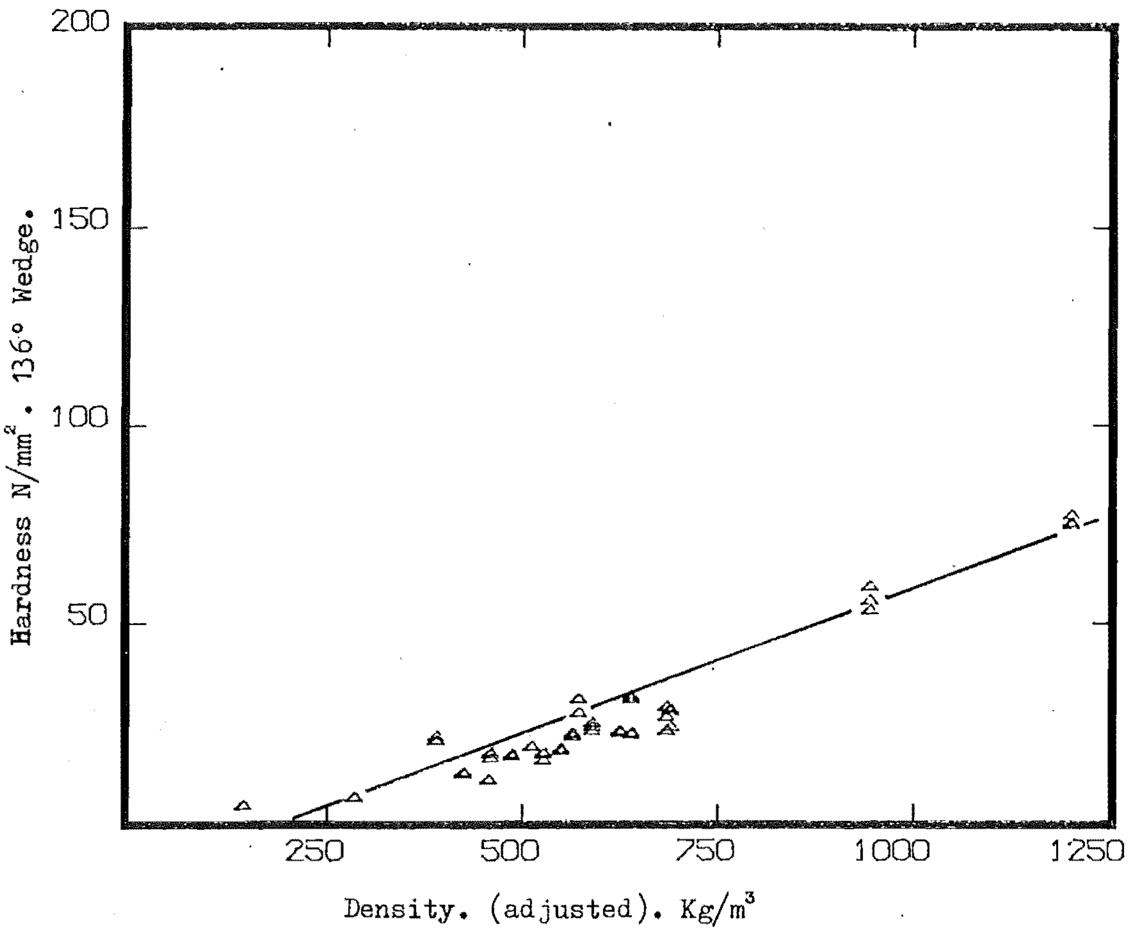


Fig. 24 - (e) and (f) Wedge Hardness versus Adjusted Density.
12% Moisture Content.



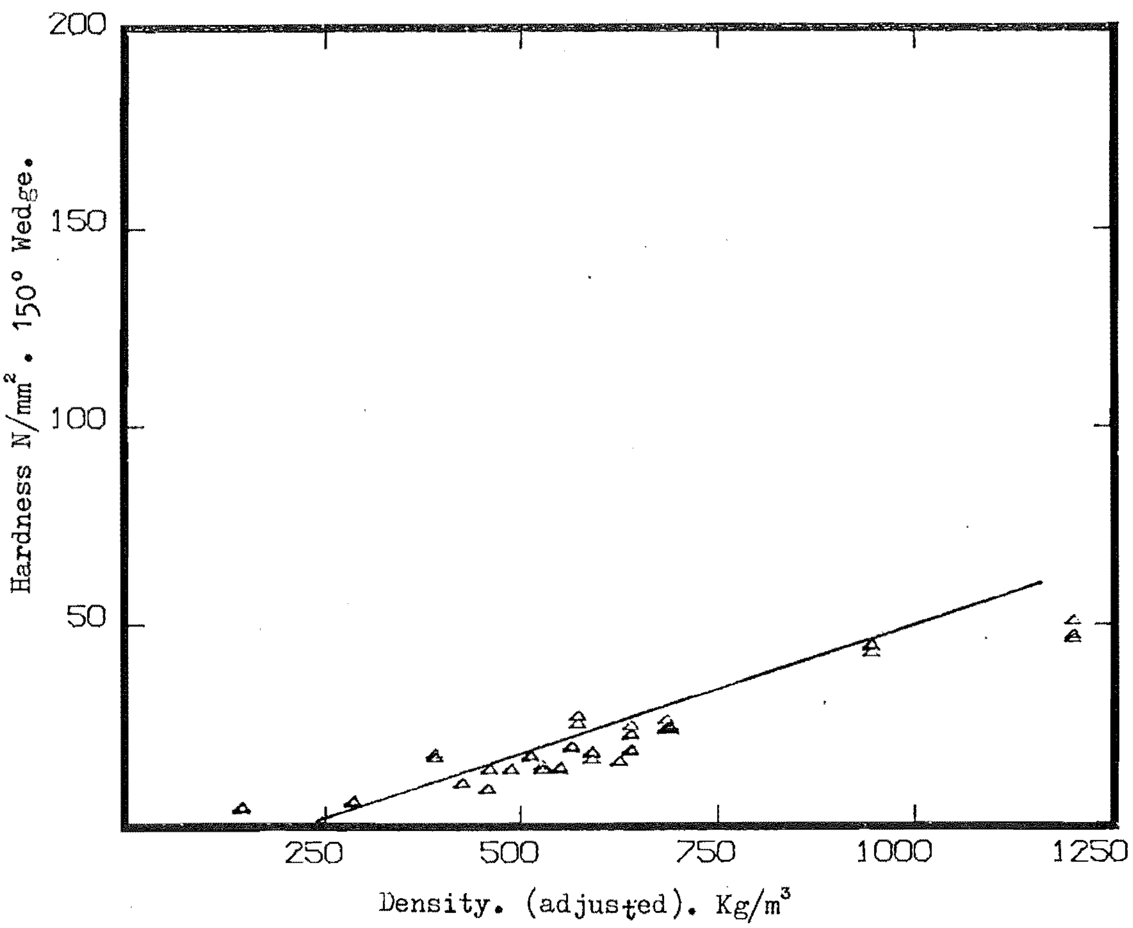
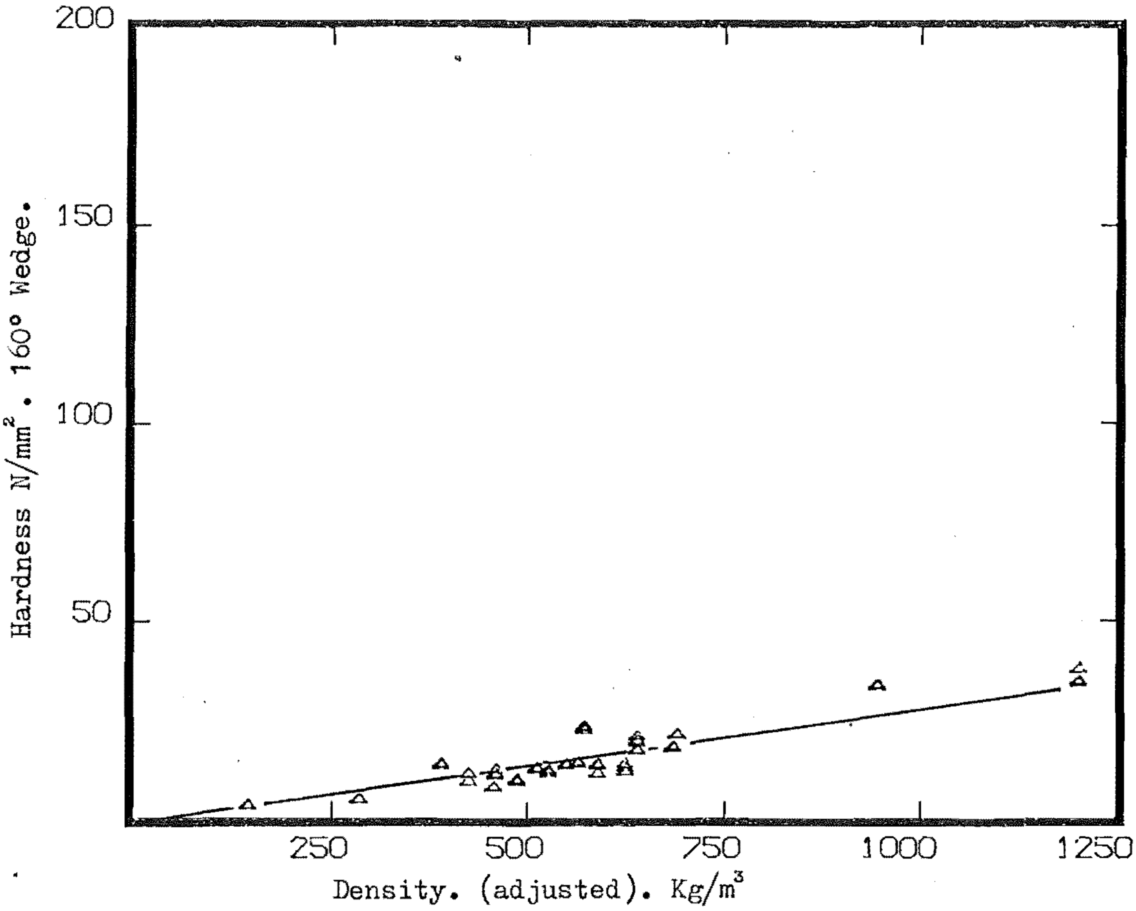


Fig. 24 - (c) and (d) Wedge Hardness versus Adjusted Density. 12% Moisture Content.



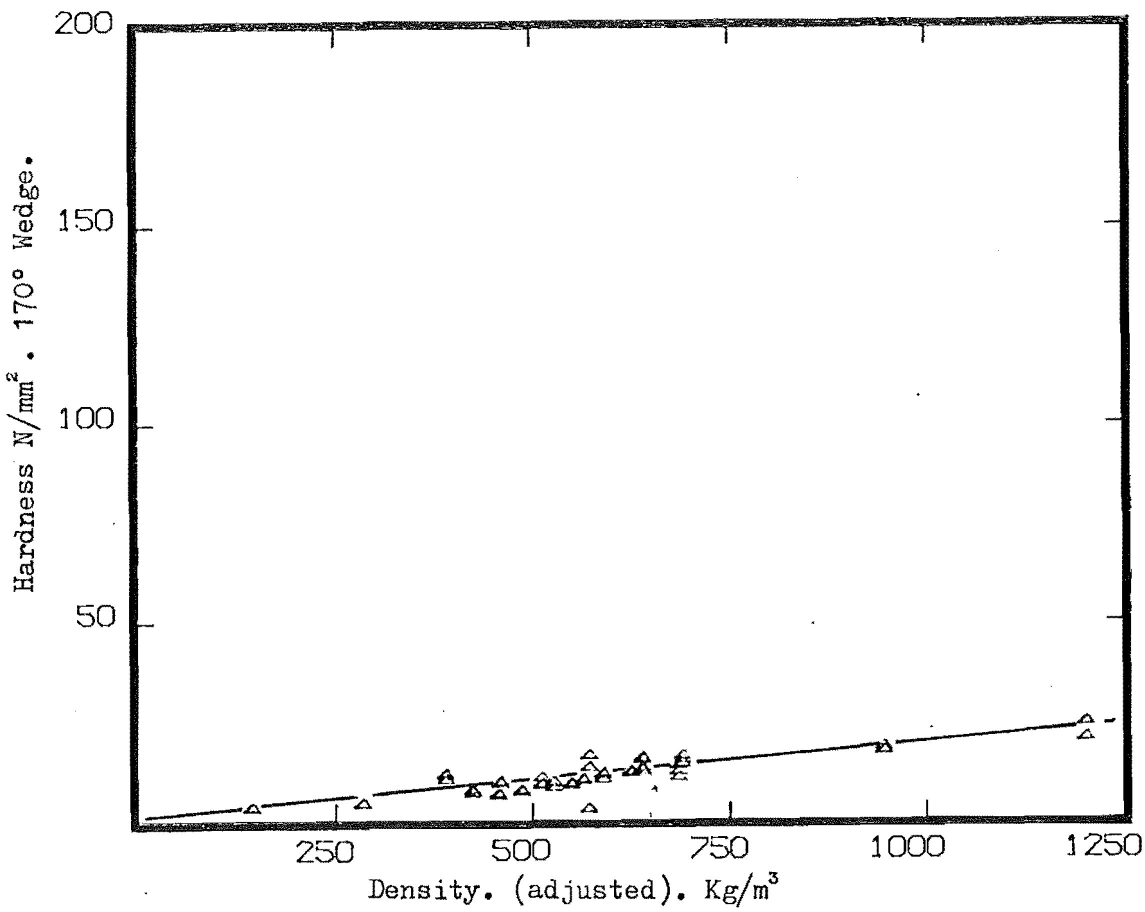


Fig. 24 - (g) and (h) Wedge Hardness versus Adjusted Density.
12% Moisture Content.

5.3.2 JANKA HARDNESS

Regressions were determined relating Janka Hardness to Wedge Hardness and to density. The results are shown in Tables 12 and below and Wedge Hardness is plotted against Janka Hardness in Fig. 25 (a) to (g).

The relationship between Janka Hardness, H_J, and adjusted density, ρ, was found to be surprisingly good. A linear equation,

$$H_J = 0.16\rho - 39.408 \qquad N/mm^2 \qquad R^2 = 0.7801$$

ρ in kg/m^3, accounted for 78% of the variation in Janka Hardness. The quadratic relationship

$$H_J = 0.044\rho + 0.00008\rho^2 \qquad N/mm^2 \quad R^2 = 0.9008$$

in kg/m^3 accounts for 90% of this variation.

In comparison with the relationship between Wedge Hardness and adjusted density the correlation for Janka in the linear case are poorer. For the quadratic case the Janka/density correlation is similar to those for the Wedge/density correlations. However, for the 160° and 170° wedge indenters, the improvement over the linear case on inclusion of the quadratic term is negligible. The suggestion here is that an equation of the form

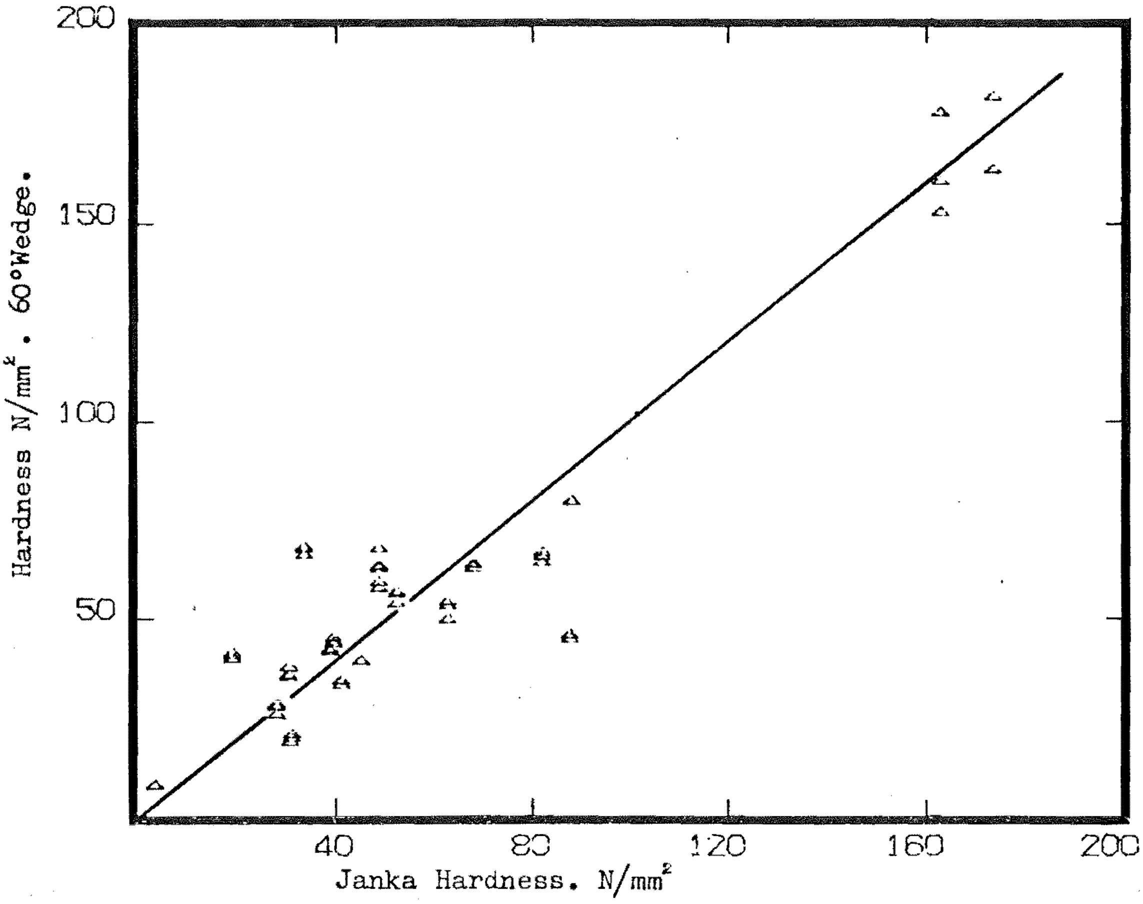
$$H = \gamma_1 \rho^n$$

will describe the relationship with density for both Wedge Hardness and Janka Hardness, with $1<n<2$. For the Janka Hardness n would be closer to 2 and for the Wedge Hardness n would tend towards 1, more so as angle increased. If this were the case, the relationship between Janka Hardness and

Wedge Hardness would show poor correlation in the linear case, being better for the lower angles than for the higher angles. This is seen to be the case in Table 12. In addition, at high angles there is no improvement in this relationship when the quadratic term is added , but an increase in the regresion coefficient is evident as wedge angle decreases.

Wedge angle (degrees)	Constant	Coefficient of x	Coefficient of x^2	R^2
Wedge Hardness, H_w, v. Janka Hardness, H_J. Air Dry.				
60	2.479	0.951	-	0.8488
90	3.350	0.645	-	0.8056
105	0.971	0.595	-	0.8183
120	3.814	0.383	-	0.7893
136	1.561	0.336	-	0.7831
150	2.979	0.223	-	0.7445
160	3.174	0.162	-	0.7176
170	3.380	0.085	-	0.6154
60	23.173	0.244	0.0039	0.8855
90	14.686	0.258	0.0022	0.8283
105	14.148	0.145	0.0025	0.8550
120	10.352	0.160	0.0012	0.8102
136	9.834	0.054	0.0016	0.8263
150	6.926	0.088	0.0008	0.7658
160	4.952	0.101	0.0003	0.7255
170	3.026	0.098	0.0000	0.6164

Table 12



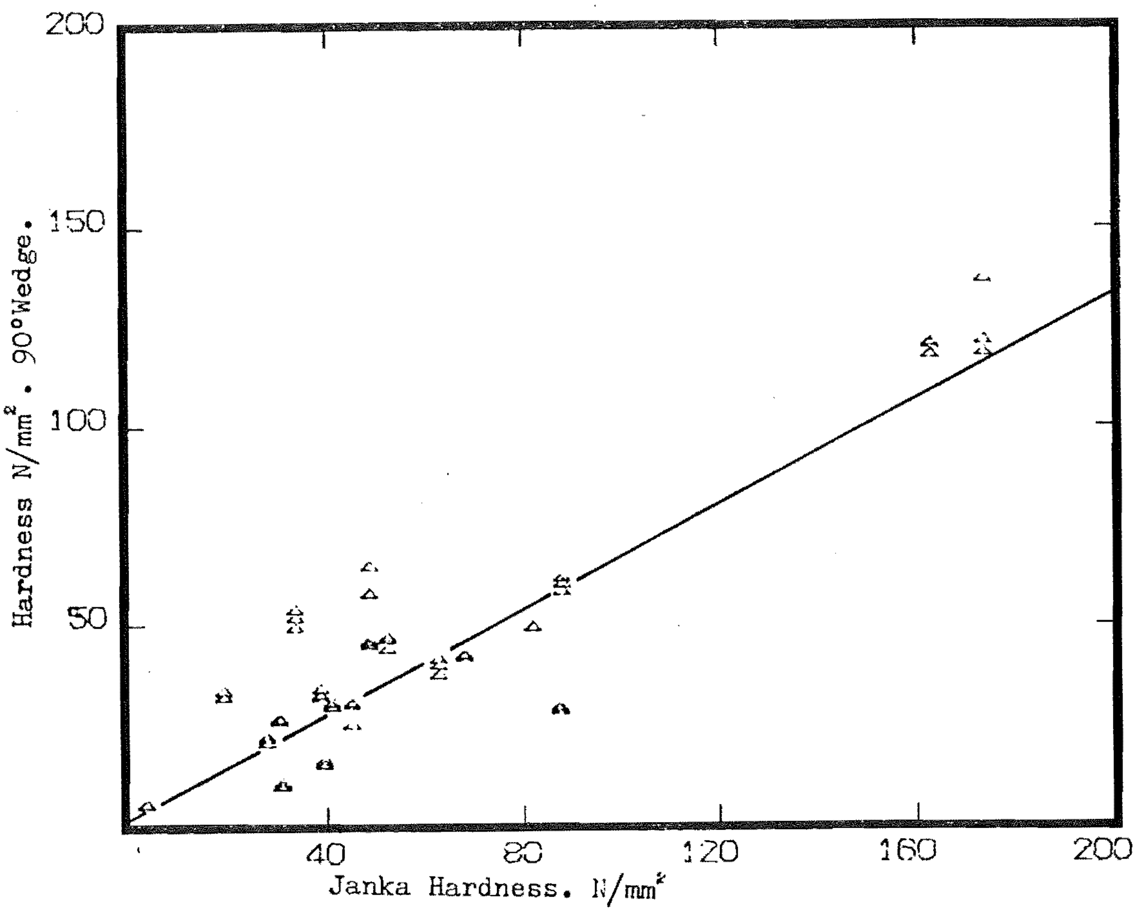
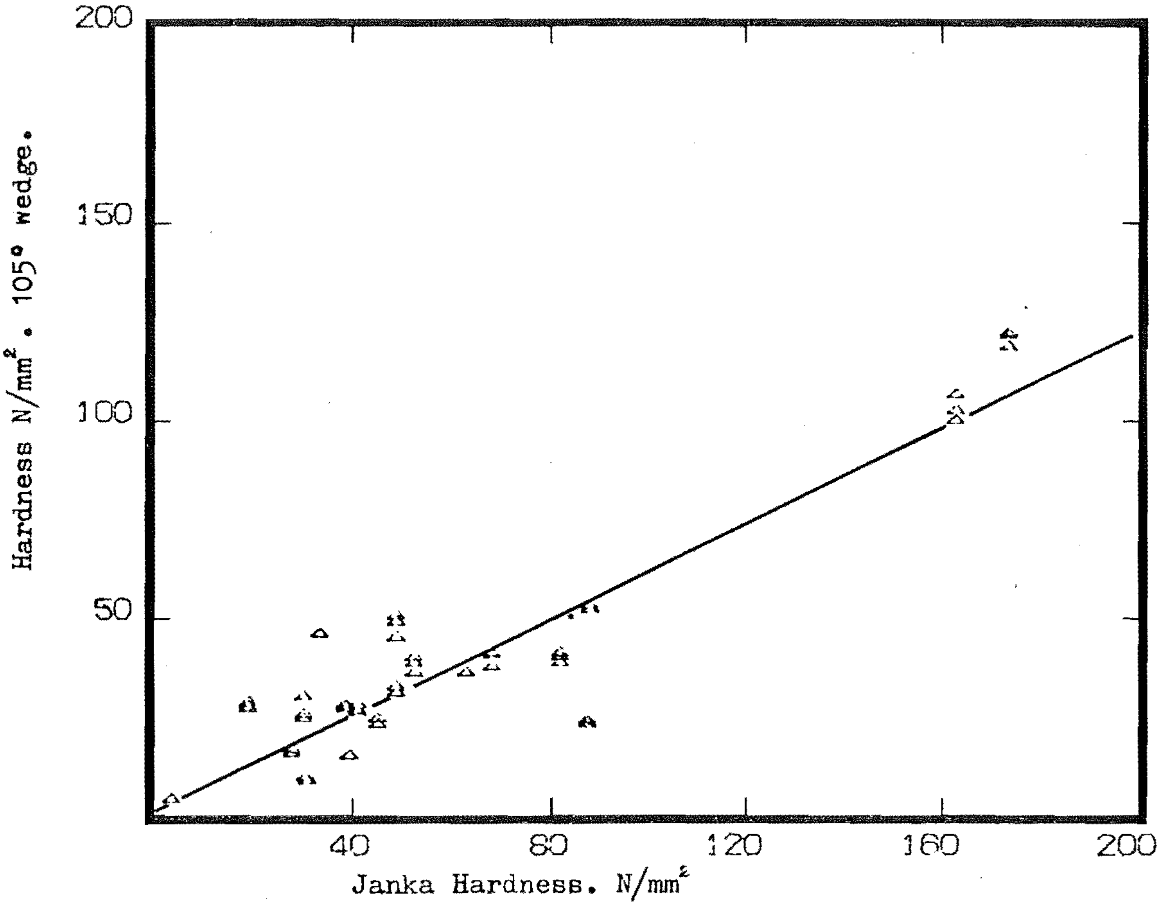


Fig. 25 - (a) and (b) Wedge Hardness versus Janka Hardness. 12% Moisture Content.



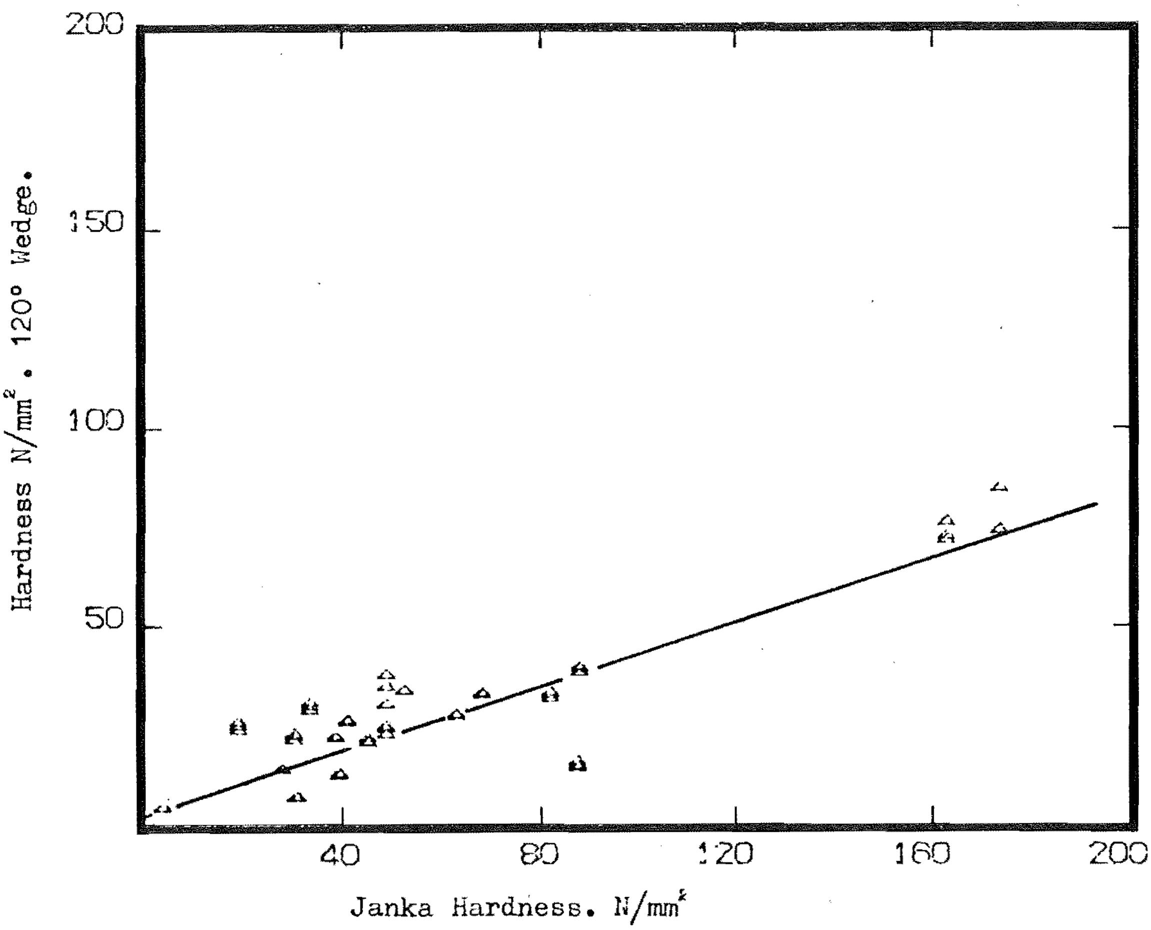
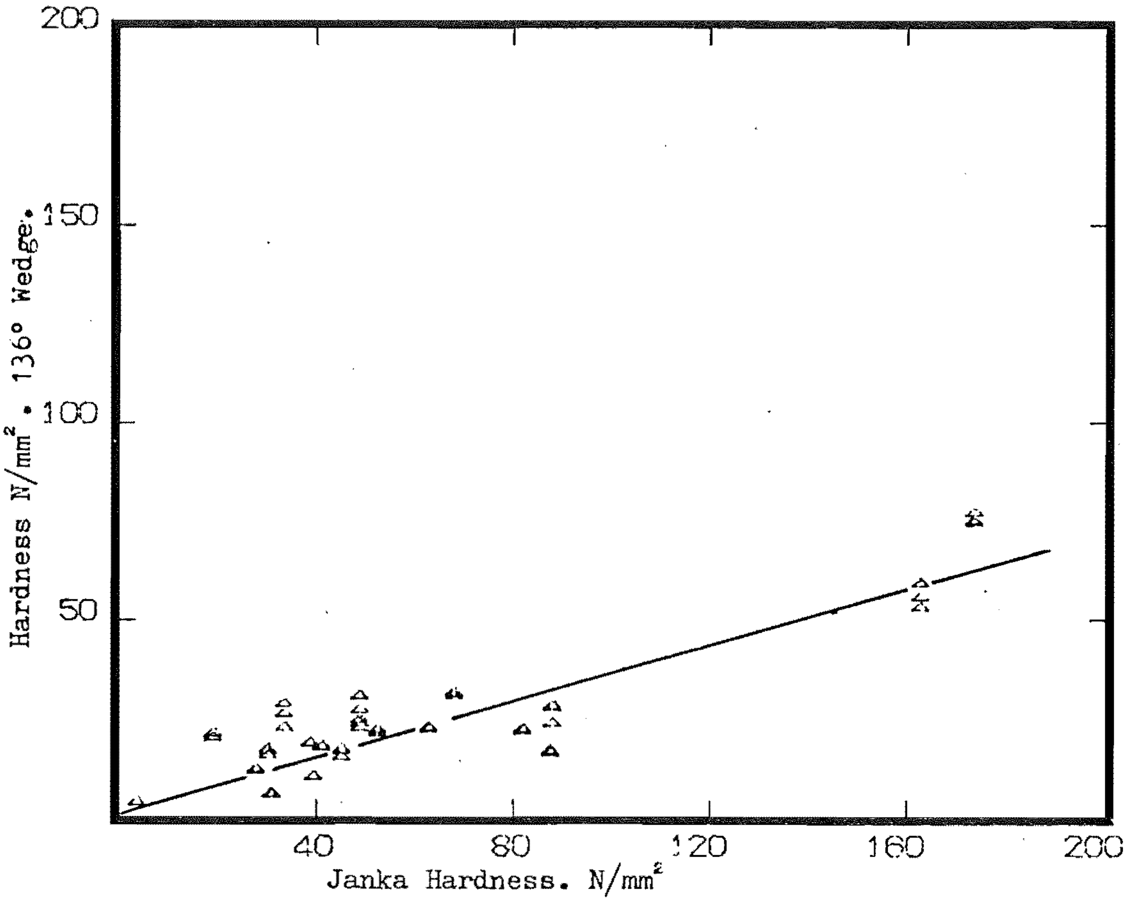


Fig. 25 - (c) and (d) Wedge Hardness versus Janka Hardness. 12% Moisture Content.



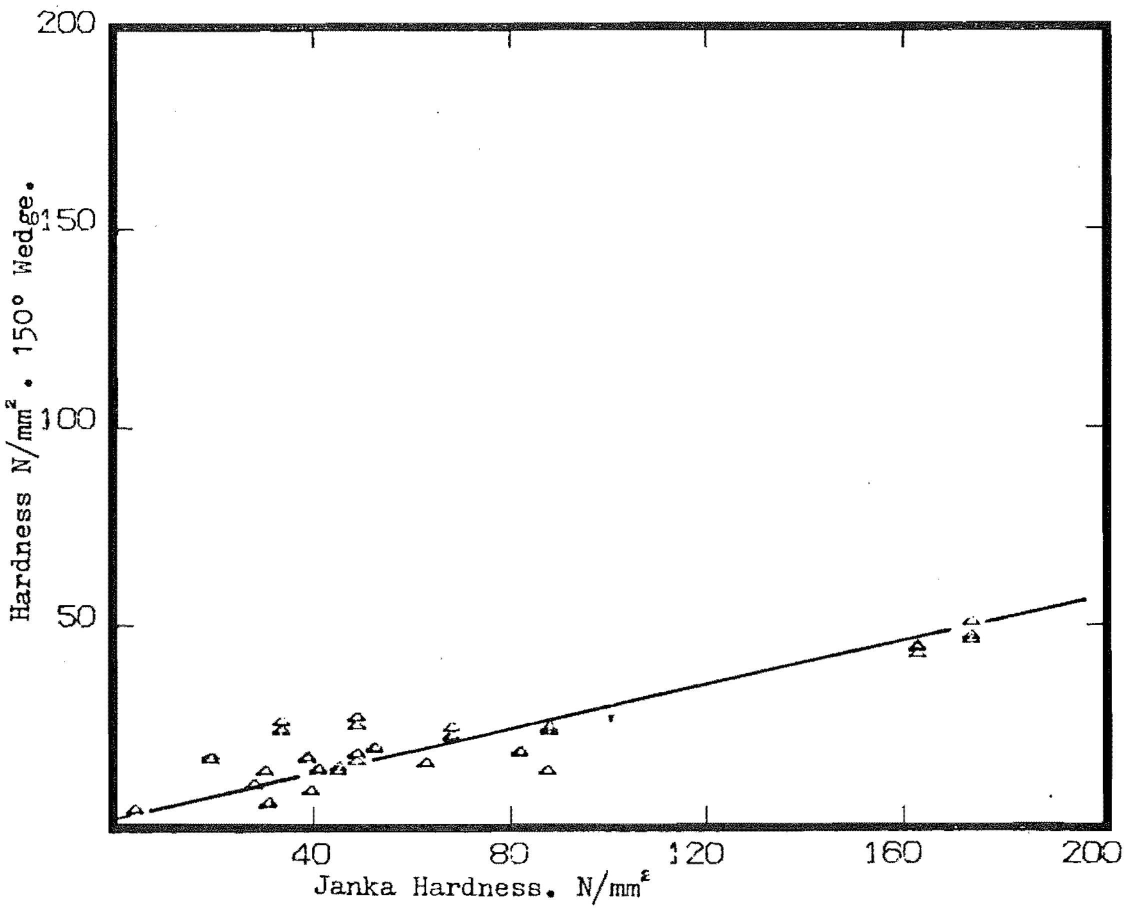
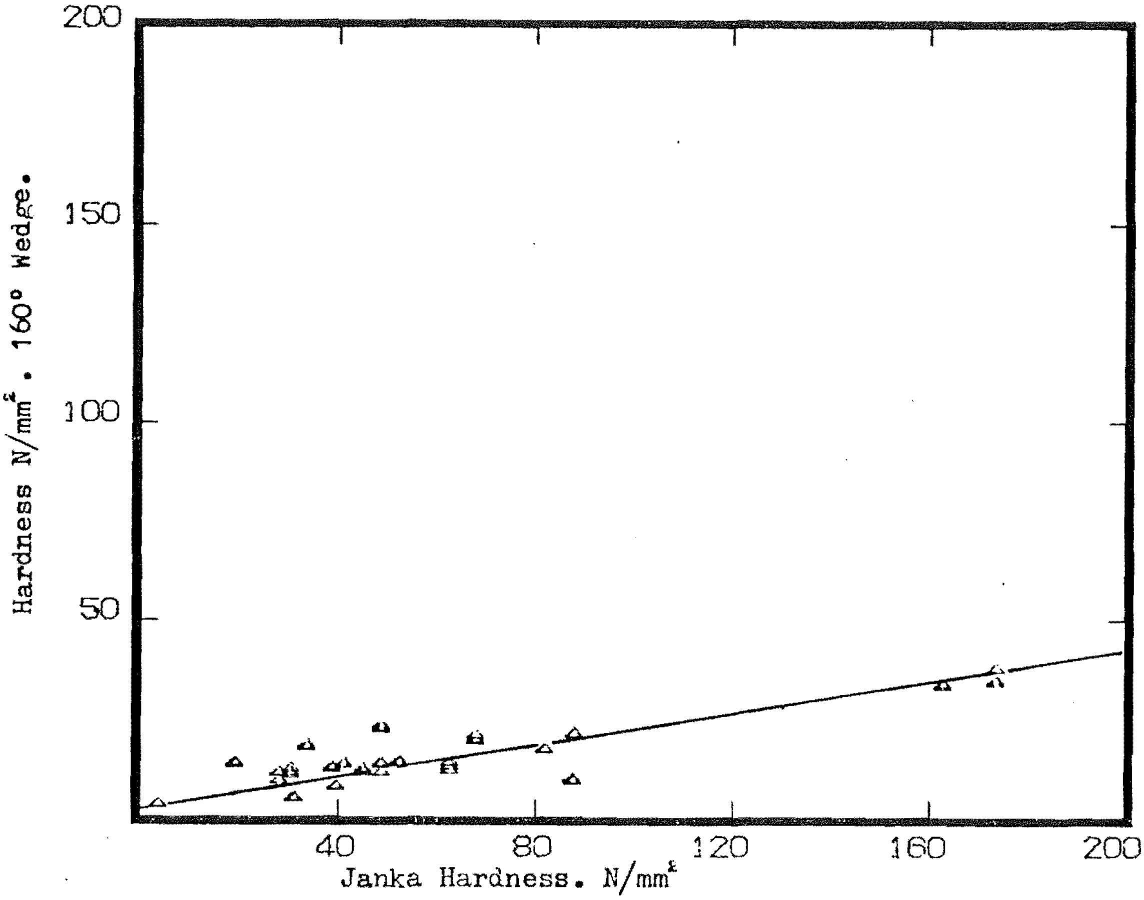


Fig. 25 - (e) and (f) Wedge Hardness versus Janka Hardness.
12% Moisture Content.



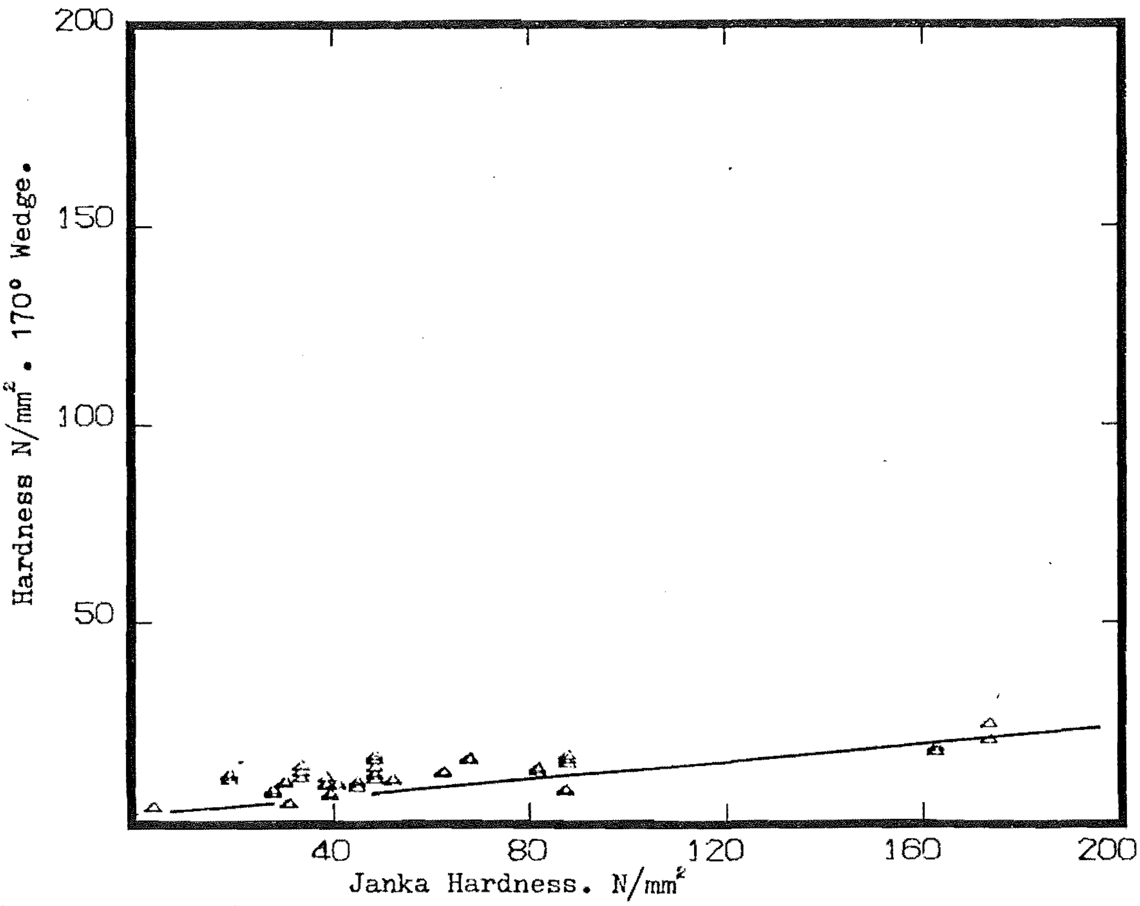


Fig. 25 - (g) and (h) Wedge Hardness versus Janka Hardness.
12% Moisture Content.

5.3.3 THE RELATIONSHIP BETWEEN WEDGE HARDNESS AND THE STRENGTH PROPERTIES OF TWENTY SPECIES OF WOOD.

(i) General

Tables 13 to 14 show relationships with Wedge Hardness derived for bending strength (modulus of rupture and modulus of elasticity), cleavage strength, shear strength and compressive strength parallel and perpendicular to the grain.

In determining these relationships it was hoped that information might be forthcoming on the type of deformation occurring under different indenter angles. It was suspected for instance, that the 60° indenter would correlate better with the cleavage strength than would the 170° indenter. This effect would be suitably demonstrated by looking at the regression coefficients for the linear and quadratic cases derived by the stepwise regression package. If there is a strong correlation between any particular property and hardness with a given angle, it is likely that inclusion of the quadratic term will not improve greatly on the linear equation. In such a case, for example, suppose that cleavage strength and Wedge Hardness for sharp angles measure closely related responses, then the regression coefficients for the correlation between cleavage and sharp angles should be higher than those for high angles.

(ii) Static Bending Strength

(a) Modulus of Rupture (MOR). Table 13.

(b) Modulus of Elasticity (MOE). Table 14.

The modulus of rupture is an indication of the ultimate strength of wood in bending. In bending, several stress types are present in the sample under test. In the upper portion of the piece, the stresses are compressive, in the lower portion the stresses are tensile. At a point midway between the upper and lower surfaces, the normal stress will be zero (though shear stress will be at a maximum). As tension increases in the lower portion the upper surface will fail by buckling under the compressive stress, usually when this is at approximately half the ultimate load in tension, and the neutral plane will move towards the lower surface. Eventually, the lower fibres will fail in tension.

The modulus of elasticity is the stress required to produce unit strain below the elastic limit. It is essentially an indication of the stress-strain characteristics of the material below a certain limit of stress. Stiffer materials have a much higher modulus of elasticity than do "springy" materials. It has been shown in an earlier section that the wedges of high angles deform by a mainly elastic mechanism. The high angle indenters which produce less severe strains and thus less readily induce plastic flow, would deform the material within its elastic deformation range - the range in which elastic modulus is measured. Materials with high elastic moduli deform over only a small range before they are strained beyond the elastic limit. Thus the indenters with sharper angles will induce plastic failure very rapidly and should correlate less well with the modulus of elasticity. This is not the case, as is seen from Table 13 . It appears that again there is no systematic trend in the values of R^2, although the values for the 170^o indenter are much lower than for the group generally. It is not apparent why this should be - though consideration of the actual plot of the points (Fig. 28) does indicate a possible answer. The regression is based on the accountability of changes in the dependent variable on changes in the independent variable. It is probable that large changes in density, the independent variable, produce very small changes in hardness - changes which statistically are not much more significant than changes brought about by natural variation in hardness at any given density value. This effect would be more pronounced if the total variation in hardness over the whole density range were small - as it is with the 170^{o} indenter. In contrast, modulus of rupture correlates very well with all angles, and the quadratic equation shows much improvement for all angles over the linear case. The relationship for modulus of elasticity with density and for modulus of rupture with density are somewhat weaker:

$$MOE \leq 0.1142 + 0.0177\rho \qquad (\rho = \text{density})$$

accounts for 70.5% of the variability of MOE with density the quadractic term was very small and did not improve the correlation.

$$MOR = 0.2595 + 0.0177\rho$$

accounts for 71.29% of the variability of modulus of rupture with density. MOR is in N/mm^2, MOE in N/mm and density, ρ, in kg/m^3.

(iii) Compressive Strength.

(a) Compression parallel to the grain. Table 15.

(b) Compression perpendicular to the grain. Table 16.

It was felt that compressive strength perpendicular to the grain would correlate very well with Wedge Hardness, particularly with the wedges with high included angles. The deformation mode underneath an angle of high angle is very close to being compression perpendicular the grain, though the stress is non-uniform in the case of the wedge. However, this proved not to be the case - this set of regression equations had the poorest correlation coefficients of all the tests carried out. The 136° and 170° indenters show particularly low linear correlation, which improves with the quadratic term, remarkably so for the 170° indenter - this shows the worst linear relationship and the best quadratic relationship. A glance at the curves shows the reason for this odd response. Three points, representing one timber with a strength of approximately 55 N/mm^2, show an extremely high value in compression perpendicular to the grain. The effect of this is sufficient to indicate a poor fit if any attempt is made to draw a straight line through the points. However, by tipping the end of the curve downwards by including a negative quadratic coefficient, the raltionship may be described remarkably well, especially in the case of the 170° indenter. The offending timber is Mapou, density 746 kg/m^3 (676 kg/m^3 after adjustment for extractives). Removal of these points gives the following regressions -

Wedge angle	Constant	Coefficient of x	Coefficient of x^2	R^2
60	8.714	3.322	-	0.8642
90	6.634	2.309	-	0.8620
105	4.437	2.095	-	0.8494
120	5.890	1.377	-	0.8484
136	4.069	1.155	-	0.7714
150	3.999	0.794	-	0.8003
160	3.886	0.586	-	0.7847
170	3.313	0.324	-	0.7186
60	13.620	2.643	0.0135	0.8672
90	9.377	1.929	0.0074	0.8639
105	7.627	1.654	0.0088	0.8526
120	6.478	1.295	0.0016	0.8487
136	5.003	1.026	0.0026	0.7722
150	4.664	0.703	0.0018	0.8012
160	3.487	0.641	-0.0011	0.7853
170	0.208	0.754	-0.0085	0.8243

(in this case, x is the compressive strength)

The relationships are much improved and is more in keeping with the expectation that side hardness would correlate well with compressive strength perpendicular to the grain. The extremely high value of this strength property for Mapou is not easily explicable, although this particular species does have a high proprtion of ray tissue (Meylan and Butterfield, 1978) which may add strength in this direction. The actual mean value of compressive strength perpendicular to the grain at 58.8 N/mm^2 is actually greater than the compressive strength parallel to the grain (41.5 N/mm^2). This is not normally the situation - wood is generally stronger in compression parallel to the grain. Indeed for the other nineteen species tested, this was found to be the case.

Compression parallel to the grain shows a reasonable correlation with Wedge Hardness. The linear regression describes the relationship well and the addition of extra terms did not provide any improvement. This is in agreement with the findings of Kollmann (see Kollmann and Cote, 1968 p.343) in relating compressive strength to density.

The compressive strength/density relationships for the twenty species tested are as follows:

Perpendicular to the grain:

$$\sigma = 0.0513\rho - 13.449 \qquad R^2 = 0.7966$$

and

$$\sigma = 0.0330\rho + 0.00001\rho^2 - 8.160 \qquad R^2 = 0.8049$$

Parallel to the grain:

$$\sigma = 0.080\rho + 5.857 \qquad R^2 = 0.8135$$

and

$$\sigma = 0.0287\rho + 0.00004\rho^2 + 20.7182 \qquad R^2 = 0.8409$$

The correlations are marginally better for some of the wedge hardness equations, but overall the Wedge Hardness/ compressive strength relationships are similar to those for compressive strength and density. It is rather strange that the 170° indenter - the one most similar to a compression test should give the weakest correlation. However, increased difficulty in measuring indentation depth accurately for large angle indenters may increase the variability of 170° wedge hardness thus weakening the relationship with other strength properties. The variability of hardness at any density value is relatively large for the 170° wedge when compared with that total variation in hardness with density for all samples.

(iv) Shear Strength parallel to the grain. Table 17

Shear failure occurs in almost any situation where wood is placed under a stress which is large enough to produce breakage. It can occur in any direction and in any position - between fibres, within cell walls - and it would be very difficult to predict where it would occur preferentially under a complex indentation deformation. However, it would be reasonable to assume that it occurs under high strains and certainly plays a part in plastic deformation, so it is likely that some form of micro-shear failure occurs under sharp indenters.

The relationship between Wedge Hardness and shear strength parallel to the grain is reasonably well accounted for by the linear relationships given in Table 17. No improvement was found with addition of a quadratic term.

The relationship between shear strength and density seems to be a little better than the wedge hardness/shear relationship. The equation

$$\sigma_s = 0.0273\rho - 0.2466 \qquad R^2 = 0.8624$$

σ_s = shear strength, N/mm^2, ρ = density kg/m^3, accounts for 86.24% of the variability of shear strength with density change,

$$\sigma_s = 0.0390\rho + 0.00001\rho^2 - 3.6127 \qquad R^2 = 0.8752$$

accounts for 87.52%, a very slight improvement. This can be compared with the values of R^2 for wedge hardness/shear relationships given in Table 17.

(v) Cleavage Strength Parallel to the Grain

Table 18

Cleavage strength is probably the most difficult of all the properties of wood to analyse. Involved in a cleavage failure are a number of factors, but basically failure is initiated as a crack at a point of stress concentration. As wood is anisotropic and inhomogeneous, propogation of a crack through the material becomes a highly complex process.

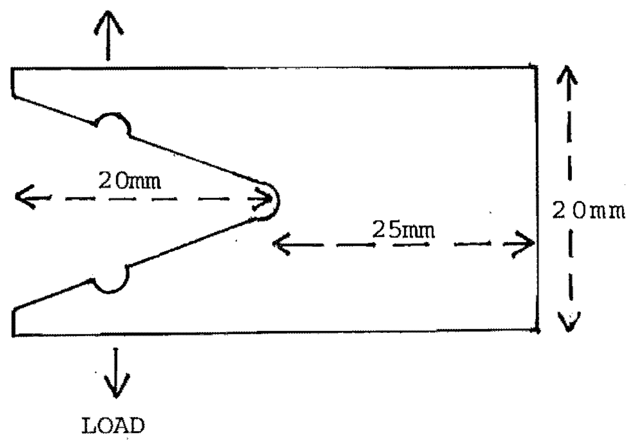


Fig. 26 - Cleavage Test sample (BS 373)

As the wood is stressed in tension across the grain, the shape of the test sample (see Fig. 26) dictates the area in which failure will occur by ensuring that a stress concentration will occur at the apex of the machined cut. When a crack appears in the strained wood the material immediately below the crack becomes relaxed and the strain energy is released. The relief of strain energy is roughly proportional to the square of the depth of the crack (Gordon, 1968, p. 107) so shallow cracks release considerably less energy than deep ones. The energy required to form the new surface is dependent only on the depth of the crack. Thus, when the crack is small it consumes more surface energy than it produces as relaxed strain energy. Under these conditions the crack does not propogate. As the crack lengthens, however, a critical length is reached where the energy from strain relaxation becomes greater than the energy required to form the two new surfaces and the crack propogates rapidly.

The presence of rows of cells with varying amounts of lignin, as well as rays and cross grain breaking up the orderly pattern, obviously complicate the situation in wood. However, this failure mechanism would be generally valid. It would be expected that indenters causing high strains and high stress concentrations would show ultimate failure points which would correlate very well with cleavage strength. None of the hardness tests were taken to the point of failure, but since microfailure of fibres inevitably occurs under the sharper wedges, these should correlate better than blunt indenters with cleavage strength. This is found to be the case.

The correlations are very good for the sharper indentations, and though lower for increasing angles, are generally very acceptable. The range is from 75.5 to 82.5% of variation in cleavage strength with hardness accounted for by the linear regression.

This does not, however, improve on the relationship between cleavage strength (σ) and density (ρ) for the same timbers. The equation

$$\sigma = 0.4903\rho - 98.6801 \qquad R^2 = 0.8509$$

describes 85% of variability of cleavage strength with density change and the following form

$$\sigma = 0.3432\rho + 0.00011\rho^2 - 56.1054 \qquad R^2 = 0.8752$$

accounts for 87.52% (σ in N/mm^2 and ρ in kg/m^3).

Wedge angle (degrees)	Constant	Coefficient of x	Coefficient of x^2	R^2
Wedge Hardness, H_w, v. Bending Strength, MOR. Air Dry.				
60	-28.348	8.362	-	0.7713
90	-21.445	6.058	-	0.8236
105	-21.359	5.549	-	0.8042
120	-10.470	3.556	-	0.7928
136	-10.419	3.086	-	0.7172
150	-5.866	2.122	-	0.7801
160	-2.855	1.499	-	0.7172
170	1.581	0.037	-	0.8073
60	29.513	-2.978	0.461	0.8445
90	11.402	-0.379	0.261	0.8716
105	14.438	-1.467	0.285	0.8706
120	10.942	-0.639	0.170	0.8498
136	11.995	-1.306	0.178	0.7922
150	4.608	0.070	0.083	0.8178
160	3.581	0.238	0.051	0.7434
170	1.609	0.037	0.000	0.8073
Wedge Hardness, H_w, v. Bending strength, MOE. Air dry.				
60	-29.619	8.570	-	0.7984
90	-22.178	6.191	-	0.8476
105	-22.346	5.700	-	0.8365
120	-10.997	3.644	-	0.8201
136	-11.464	3.218	-	0.7687
150	-6.275	2.184	-	0.8137
160	-3.281	1.556	-	0.7610
170	0.107	0.809	-	0.6577
60	30.080	-2.852	0.453	0.8726
90	9.825	0.068	0.243	0.8910
105	13.752	-1.206	0.274	0.9008
120	8.708	-0.126	0.149	0.8660
136	12.422	-1.351	0.181	0.8497
150	4.065	0.206	0.078	0.8486
160	3.027	0.349	0.048	0.7849
170	0.916	0.655	0.006	0.6589

Table 13 and 14

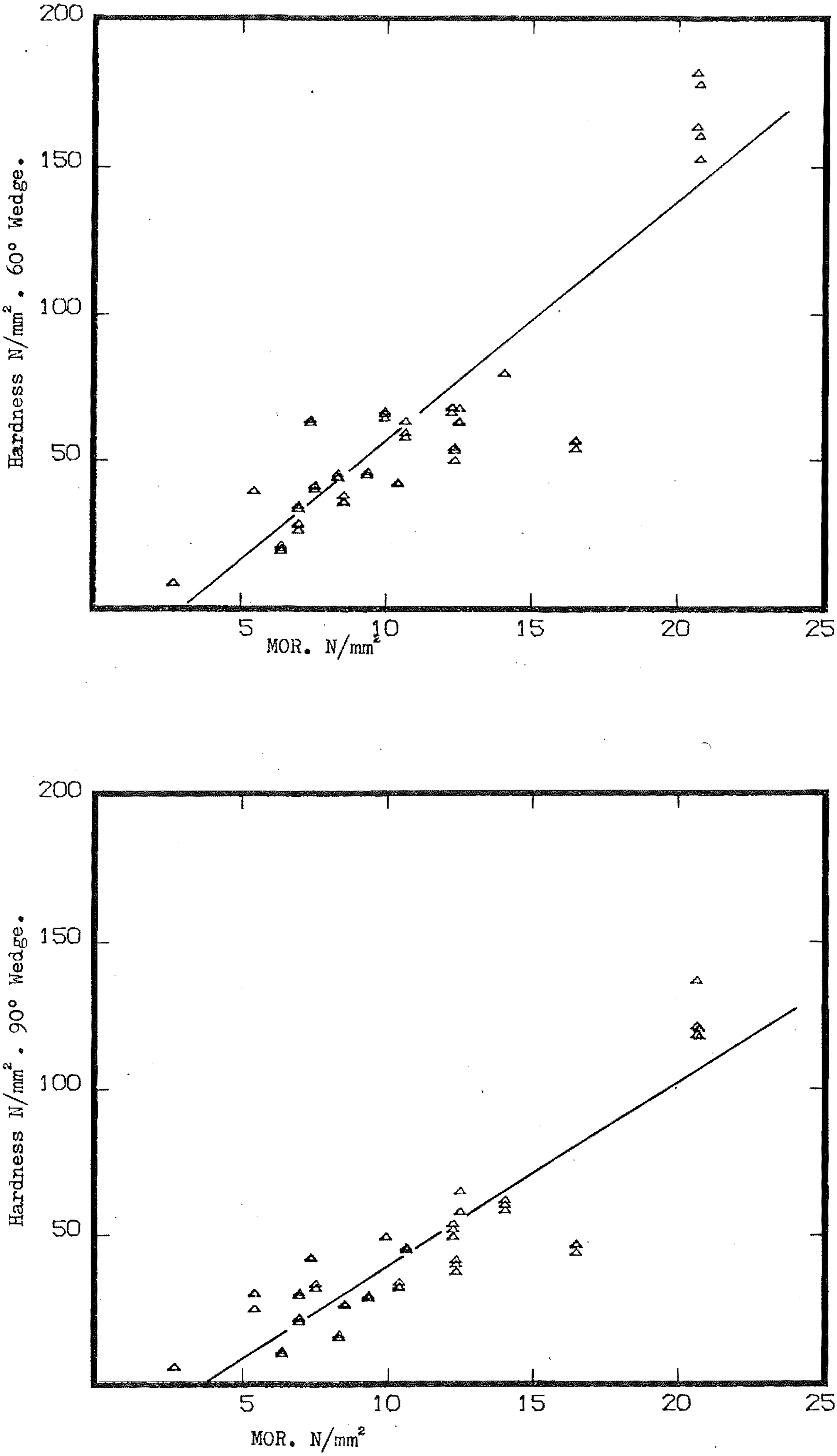
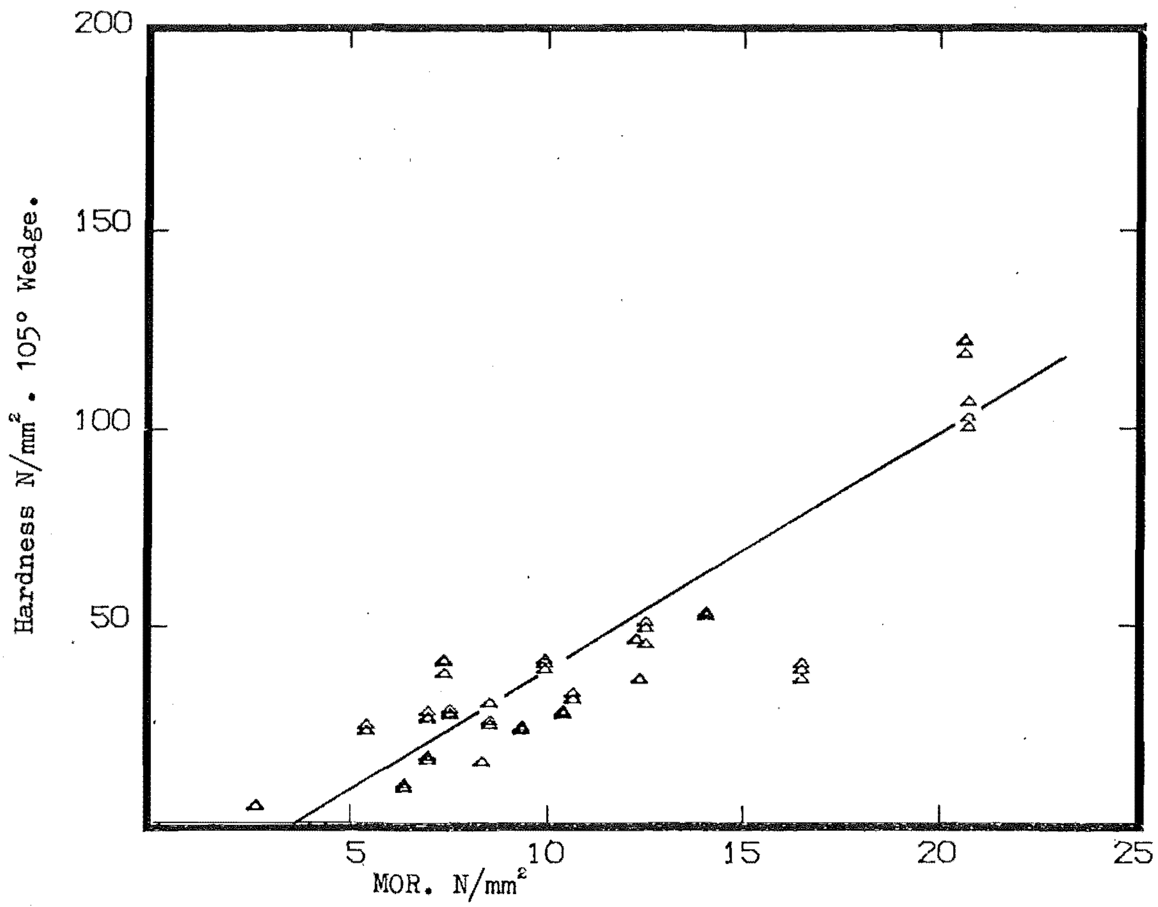


Fig. 27 - (a) and (b) Wedge Hardness versus Modulus of Rupture in Bending.



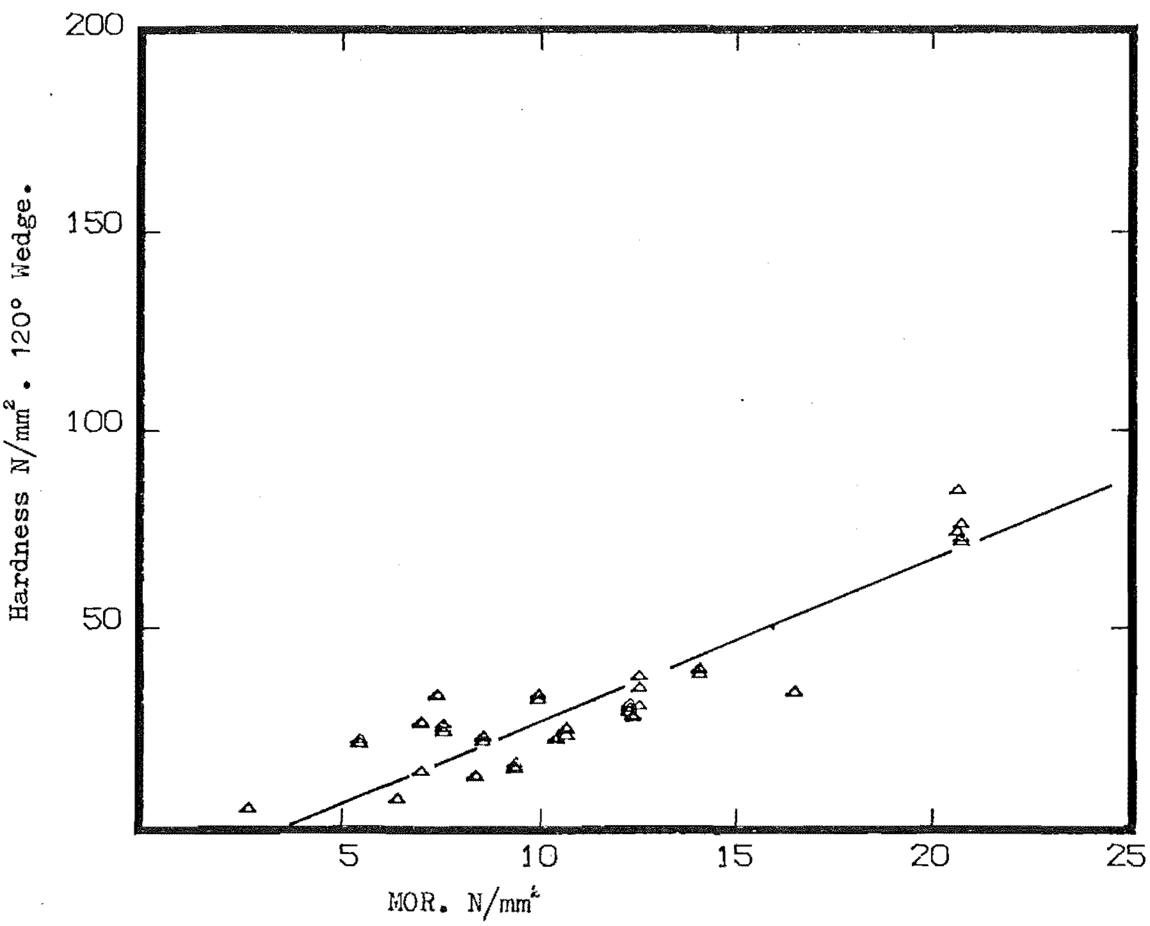
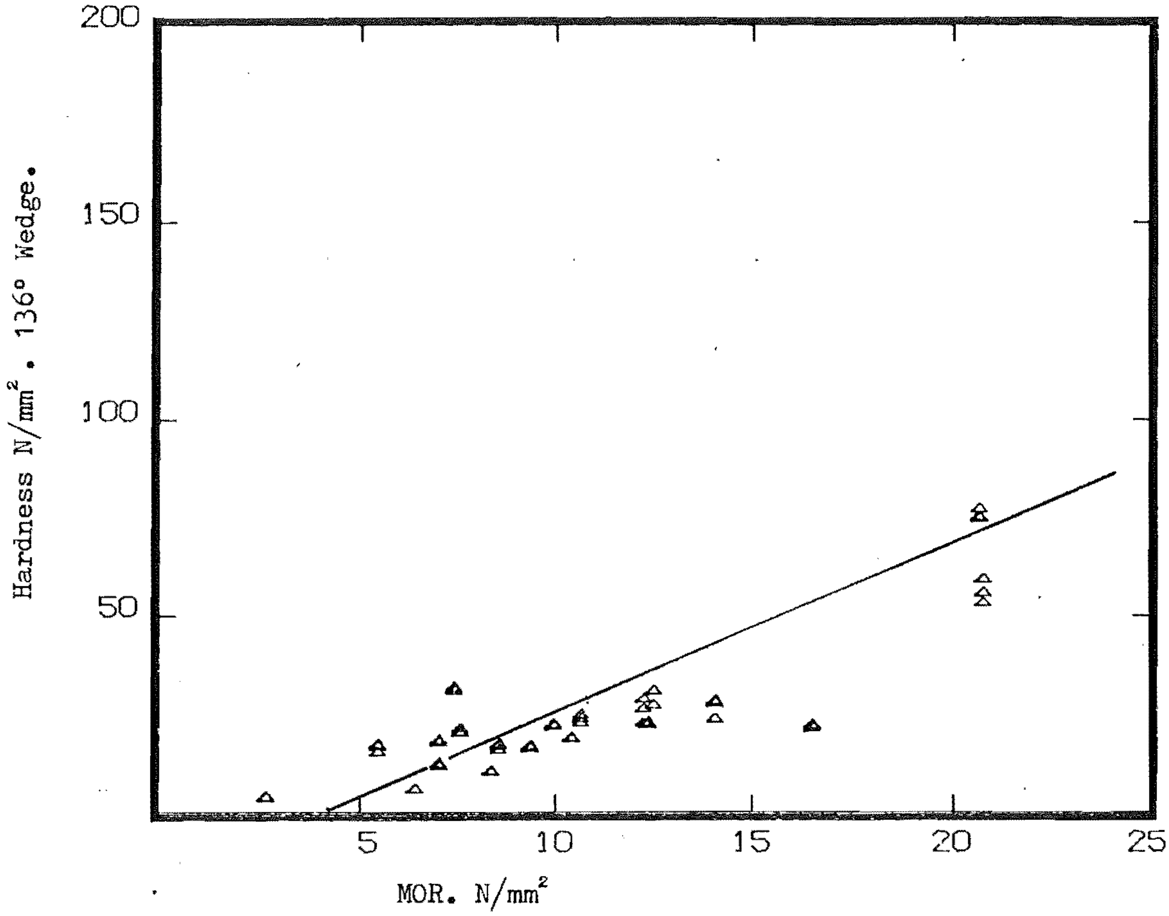


Fig. 27 - (c) and (d) Wedge Hardness versus Modulus of Rupture in Bending.



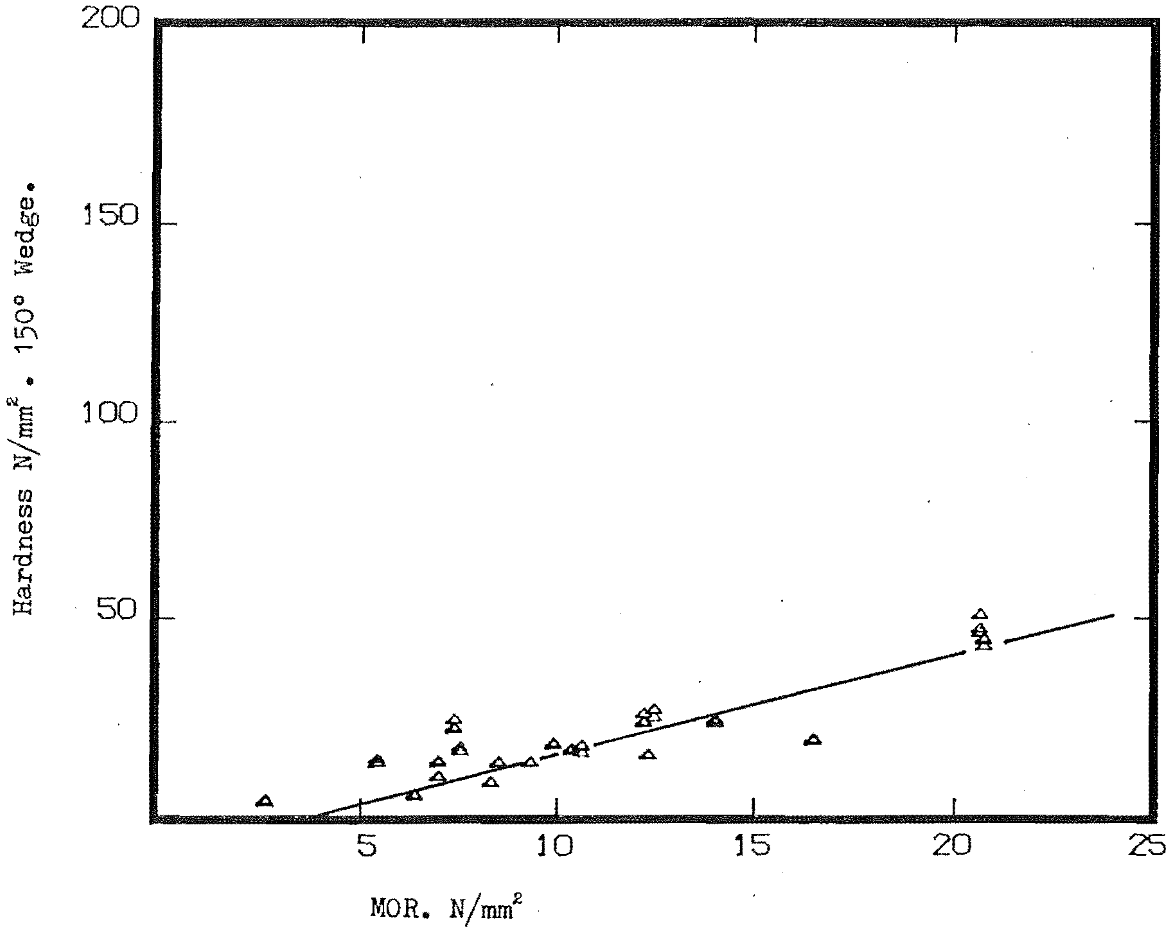
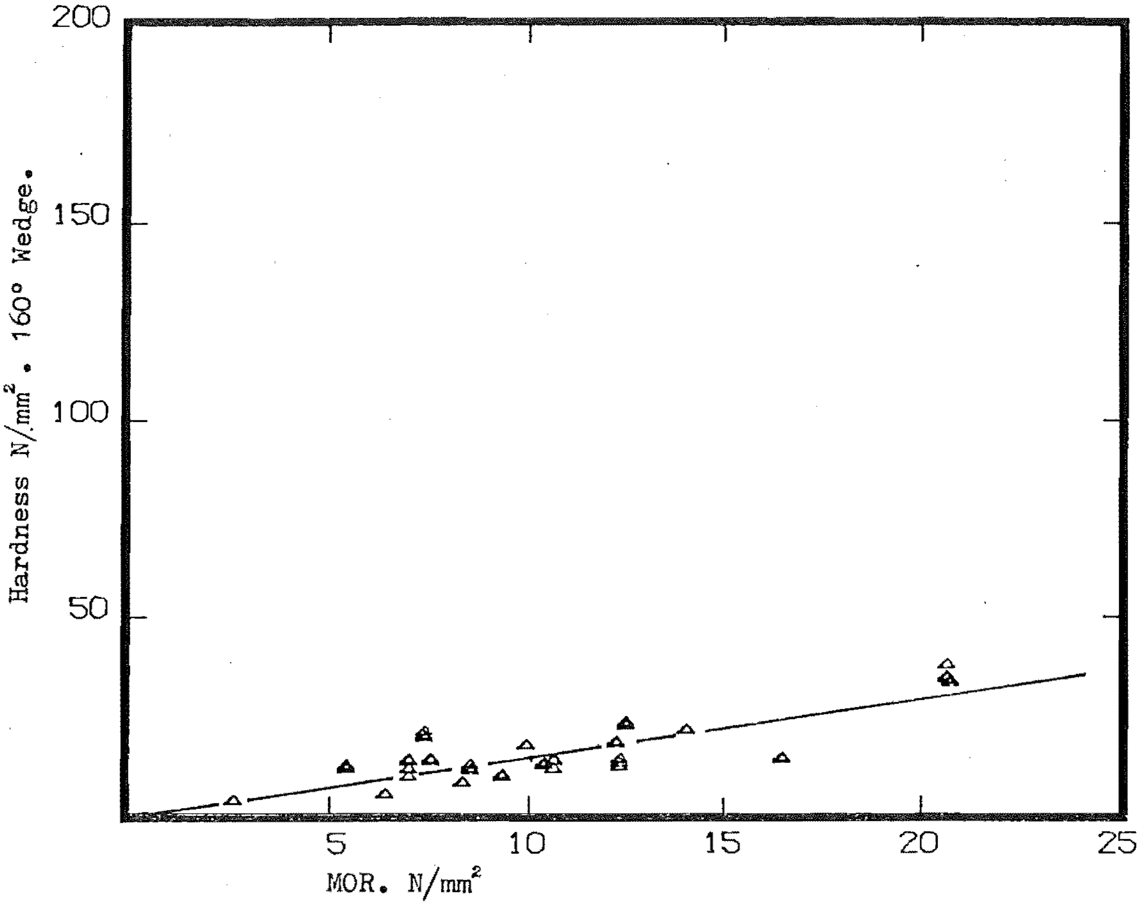


Fig. 27 - (e) and (f) Wedge Hardness versus Modulus of Rupture in Bending.



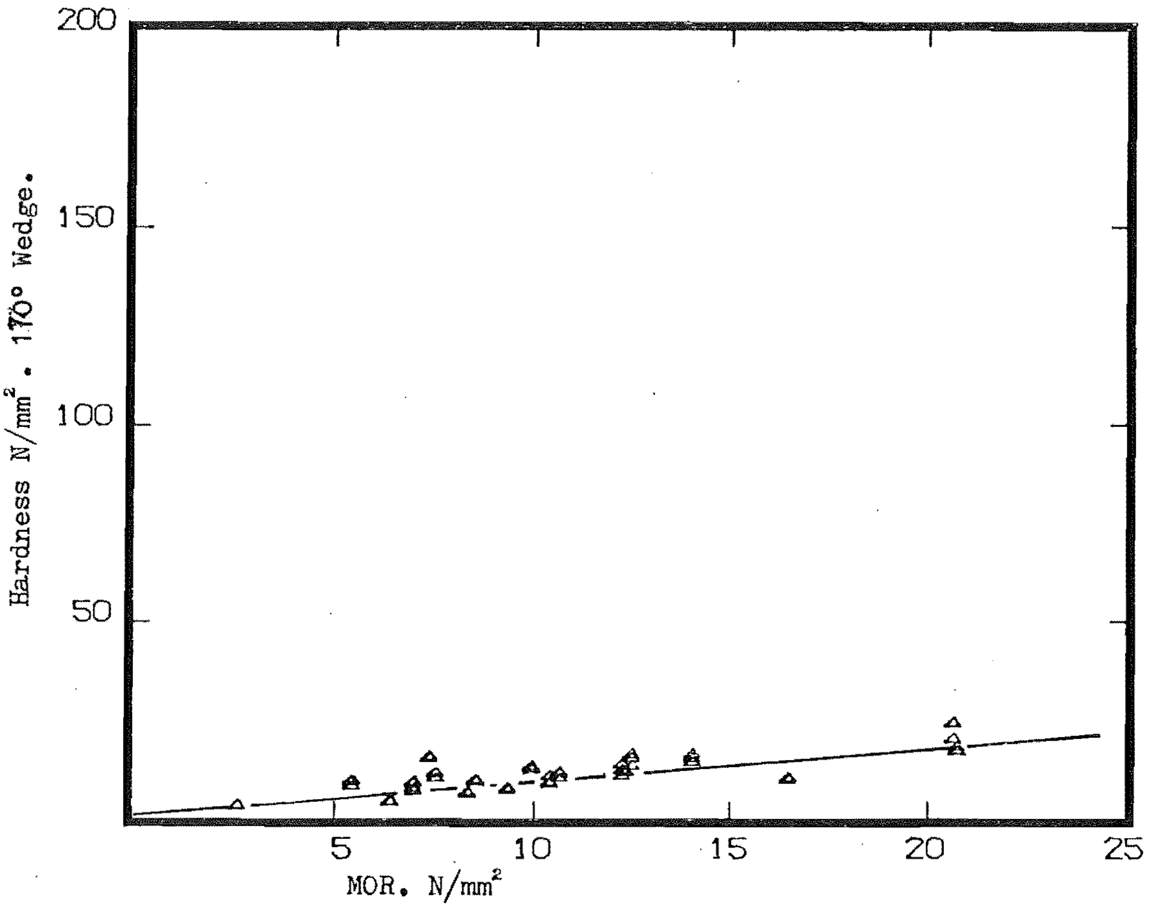
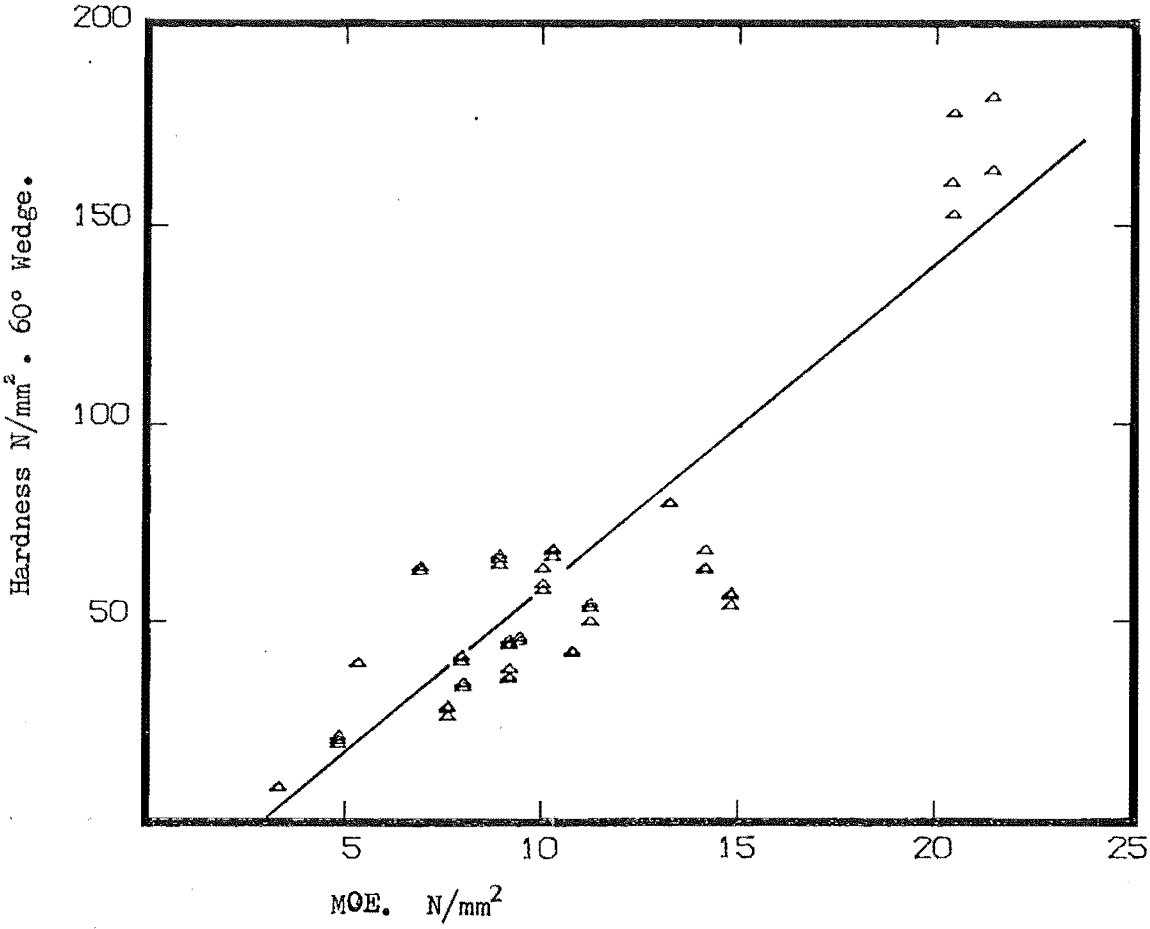


Fig. 27 - (g) and (h) Wedge Hardness versus Modulus of Rupture in Bending.



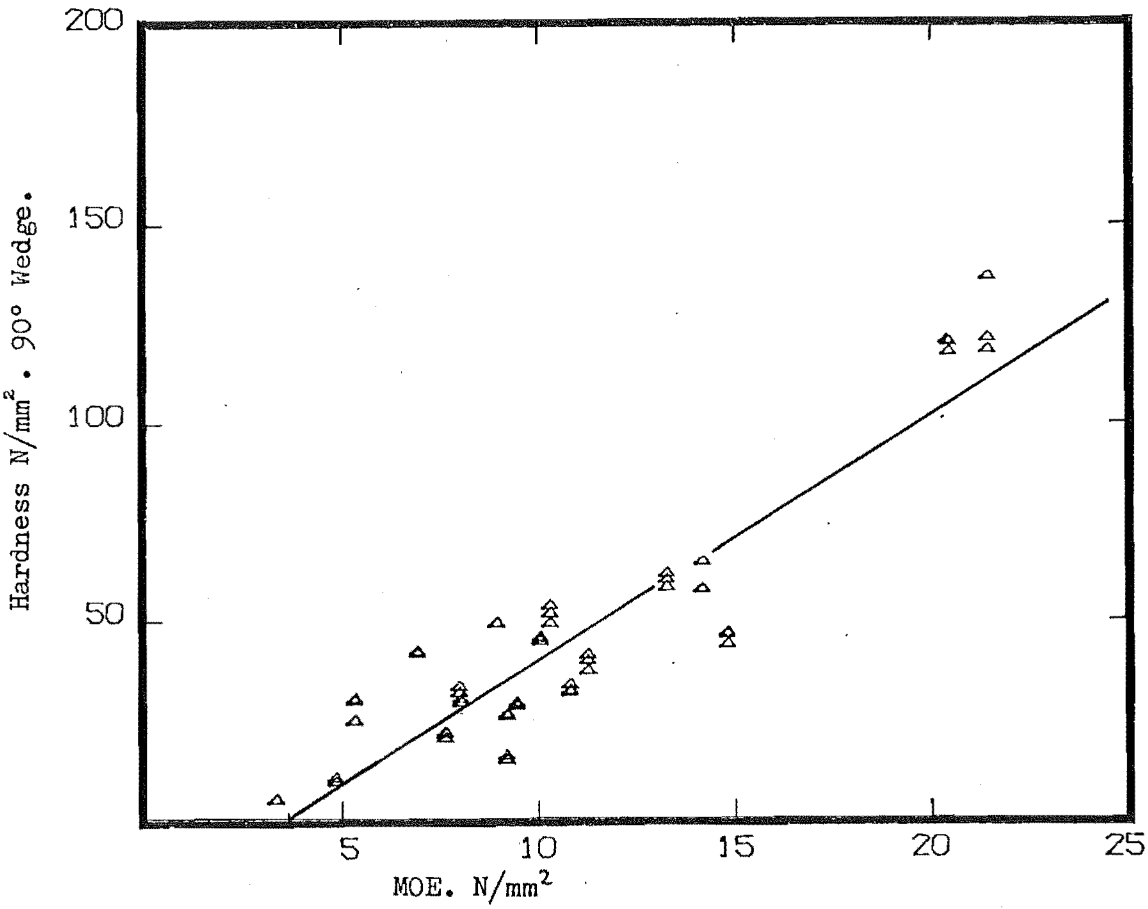
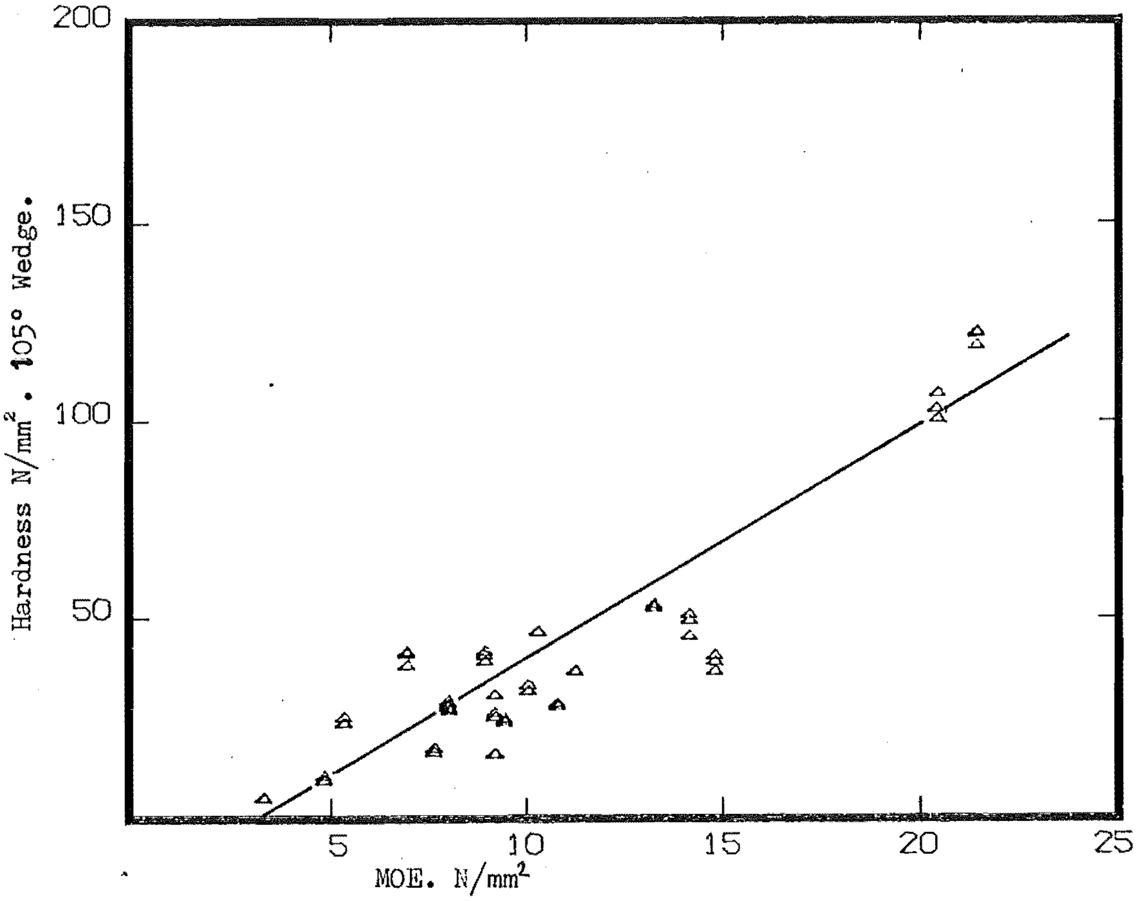


Fig. 28 - (a) and (b) Wedge Hardness versus Modulus of Elasticity in Bending. 12% Moisture Content.



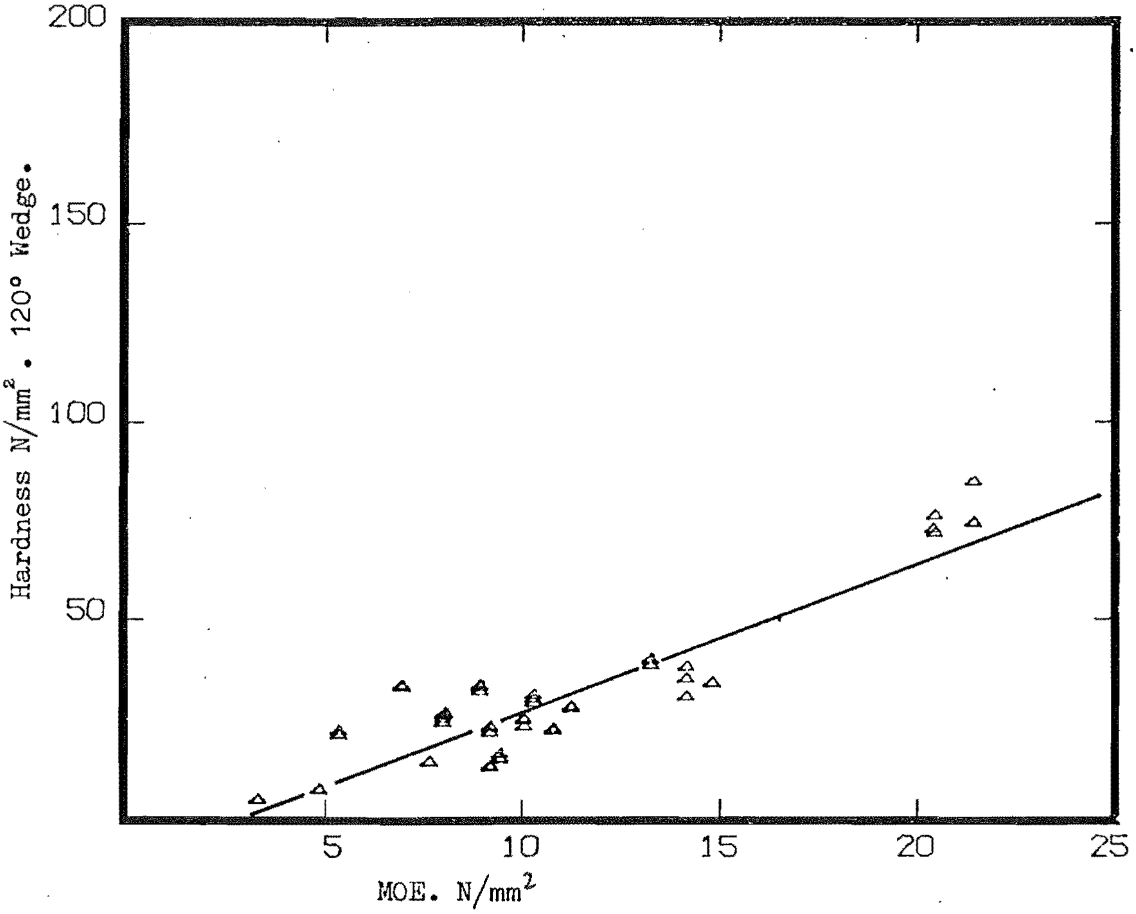
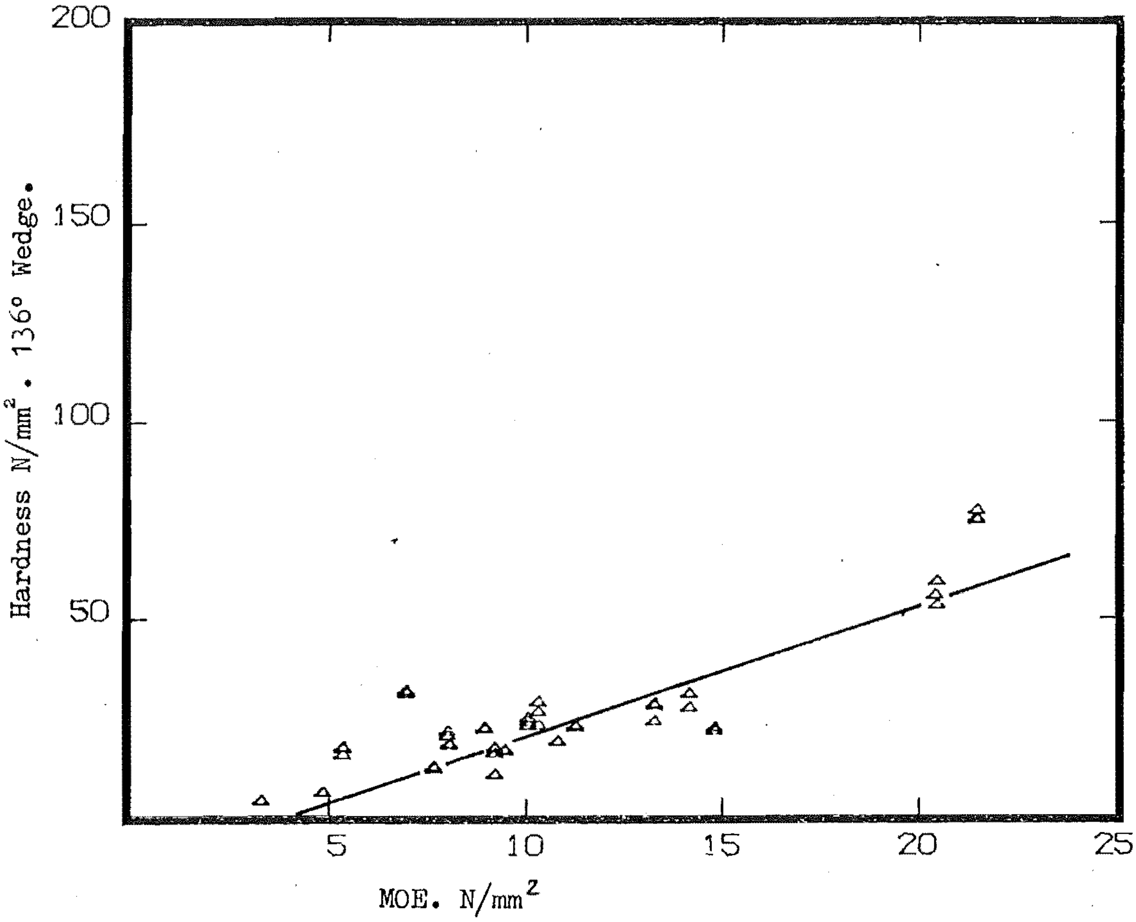


Fig. 28 - (c) and (d) Wedge Hardness versus Modulus of Elasticity in Bending. 12% Moisture Content.



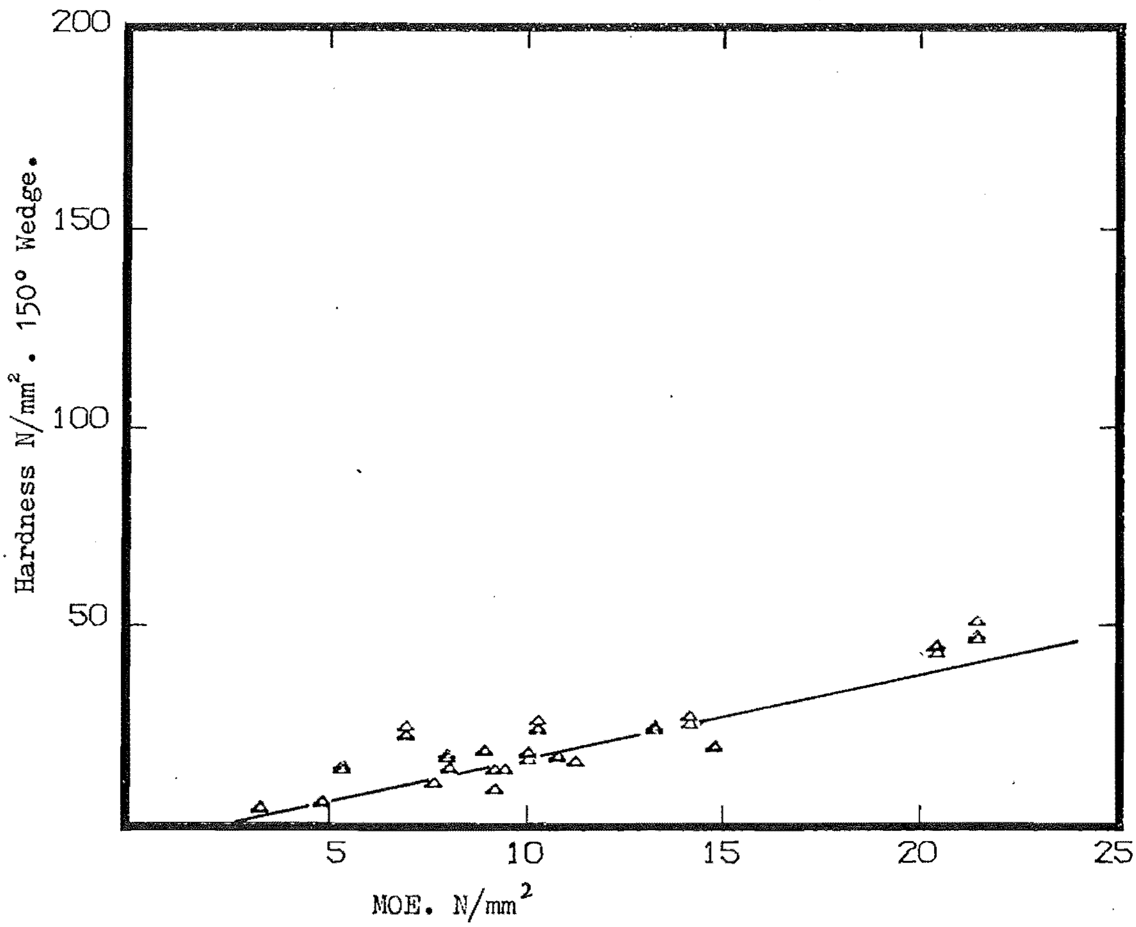
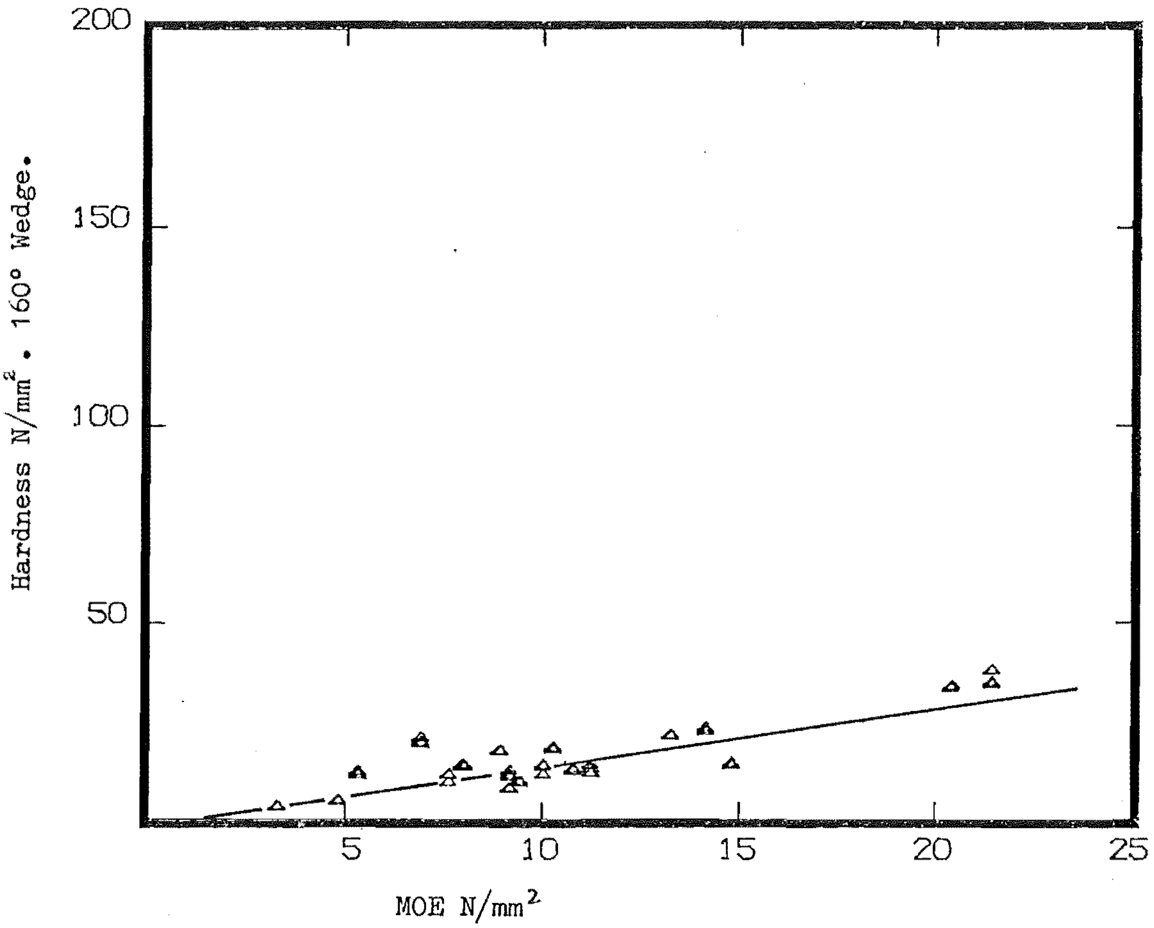


Fig. 28 - (e) and (f) Wedge Hardness versus Modulus of Elasticity in Bending. 12% Moisture Content.



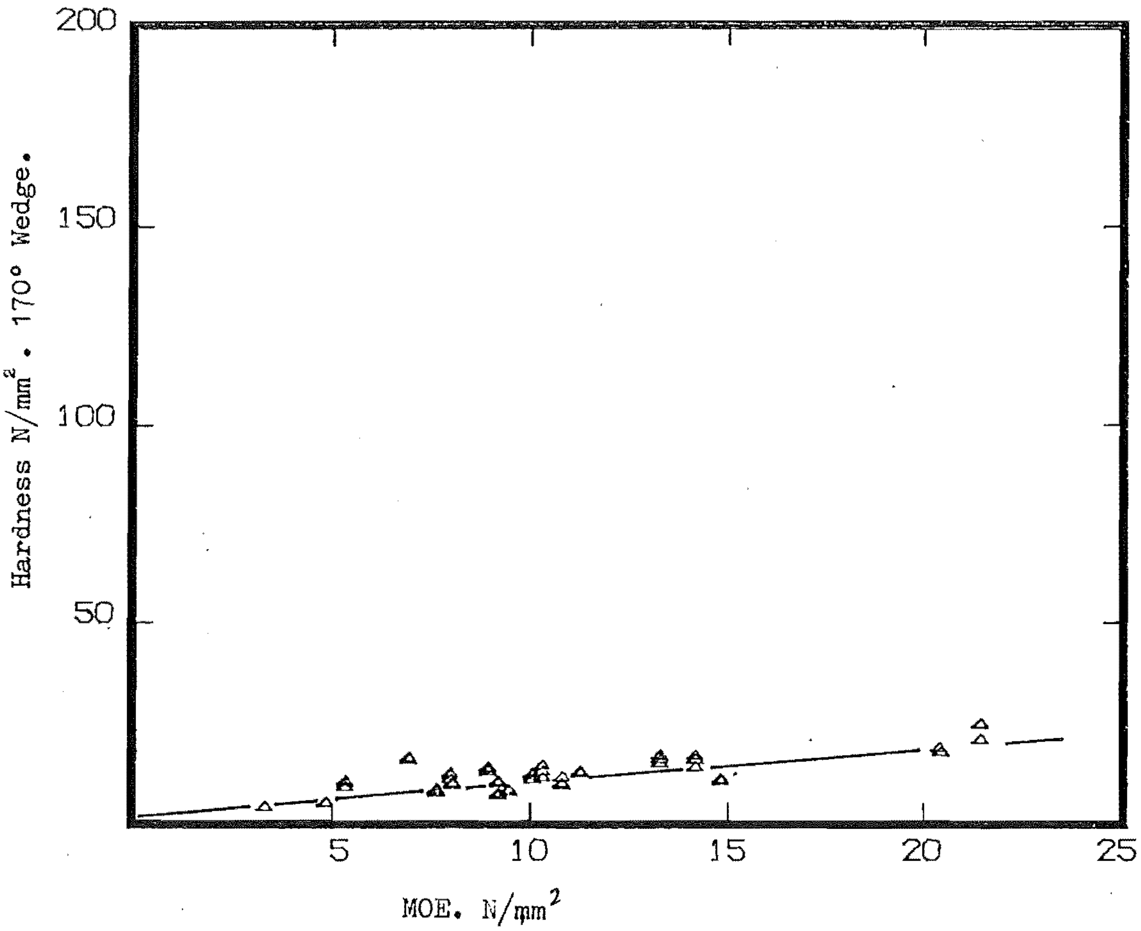
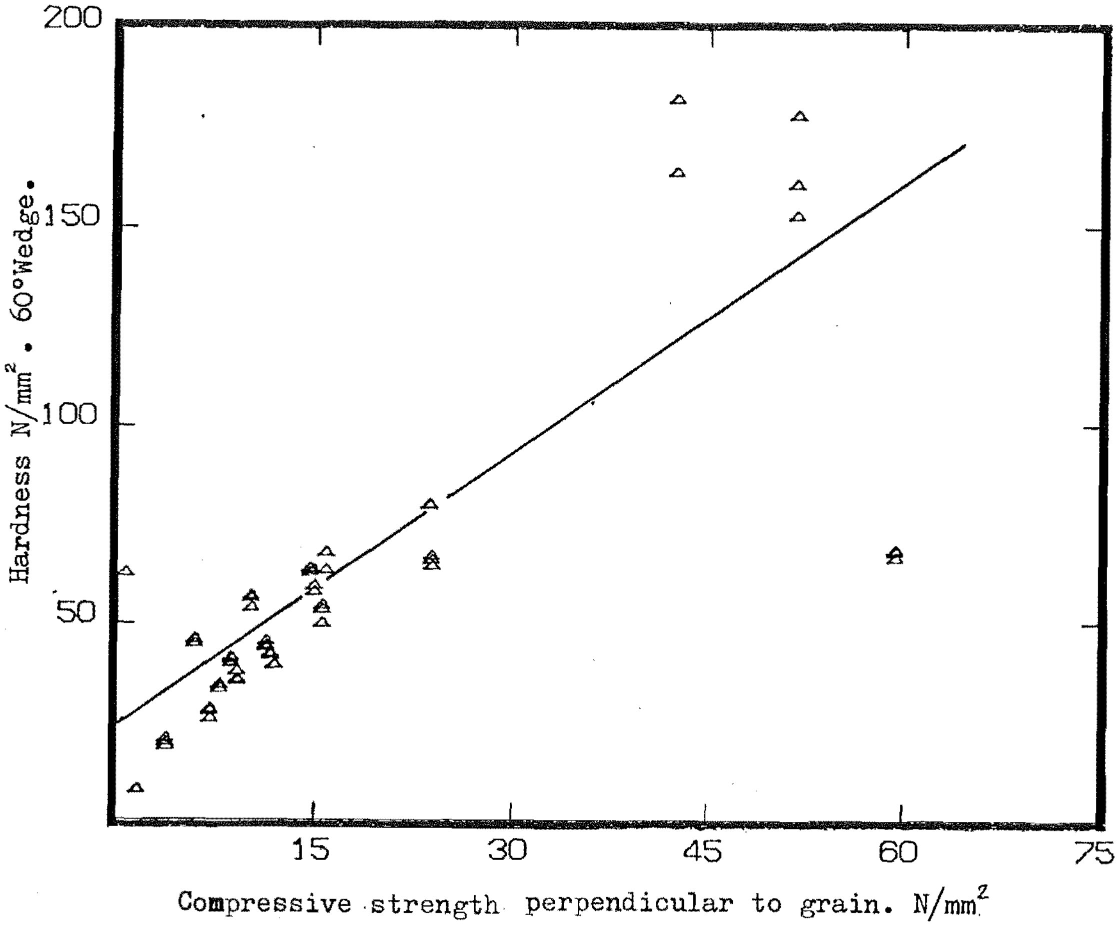


Fig. 28 - (g) and (h) Wedge Hardness versus Modulus of Elasticity in Bending. 12% Moisture Content.

Wedge angle (degrees)	Constant	Coefficient of x	Coefficient of x^2	R^2
Wedge Hardness, H_w, v. Compression perpendicular, σ_c. Air dry.				
60	20.757	2.152	-	0.5784
90	14.447	1.537	-	0.6085
105	11.475	1.402	-	0.6047
120	11.026	0.876	-	0.5491
136	8.177	0.751	-	0.5209
150	6.327	0.559	-	0.6243
160	5.736	0.399	-	0.5801
170	4.786	0.207	-	0.4808
60	-10.610	6.076	-0.0672	0.6983
90	-8.440	4.401	-0.0490	0.7400
105	-8.506	3.902	-0.0428	0.7246
120	-4.131	2.773	-0.0324	0.7094
136	-4.031	2.279	-0.0260	0.6550
150	-1.405	1.526	-0.0165	0.7407
160	-1.293	1.279	-0.0150	0.7551
170	-0.508	0.869	-0.0113	0.7873
Wedge Hardness, H_w, v. Compression parallel to grain, σ_c. Air dry.				
60	-51.656	2.149	-	0.8874
90	-35.626	1.503	-	0.8938
105	-34.794	1.382	-	0.9038
120	-19.342	0.893	-	0.8762
136	-18.915	0.786	-	0.8765
150	-11.009	0.529	-	0.8599
160	-7.119	0.387	-	0.8380
170	-2.189	0.207	-	0.7403
Wedge Hardness, v. Shear strength, τ. Air dry.				
60	-35.644	6.094	-	0.7765
90	-25.435	4.327	-	0.8065
105	-25.894	4.010	-	0.8282
120	-14.205	2.630	-	0.8280
136	-12.849	2.216	-	0.7576
150	-8.155	1.572	-	0.8258
160	-5.158	1.159	-	0.8165
170	-1.756	0.646	-	0.7555
Wedge Hardness, H_w, v. Cleavage strength, σ_{cl}. Air dry.				
60	-5.032	0.351	-	0.8061
90	-2.631	0.243	-	0.7974
105	-4.919	0.226	-	0.8254
120	-0.237	0.147	-	0.8120
136	-1.923	0.128	-	0.8007
150	0.333	0.087	-	0.7955
160	1.095	0.064	-	0.7875
170	1.893	0.036	-	0.7671

Tables 15 - 18



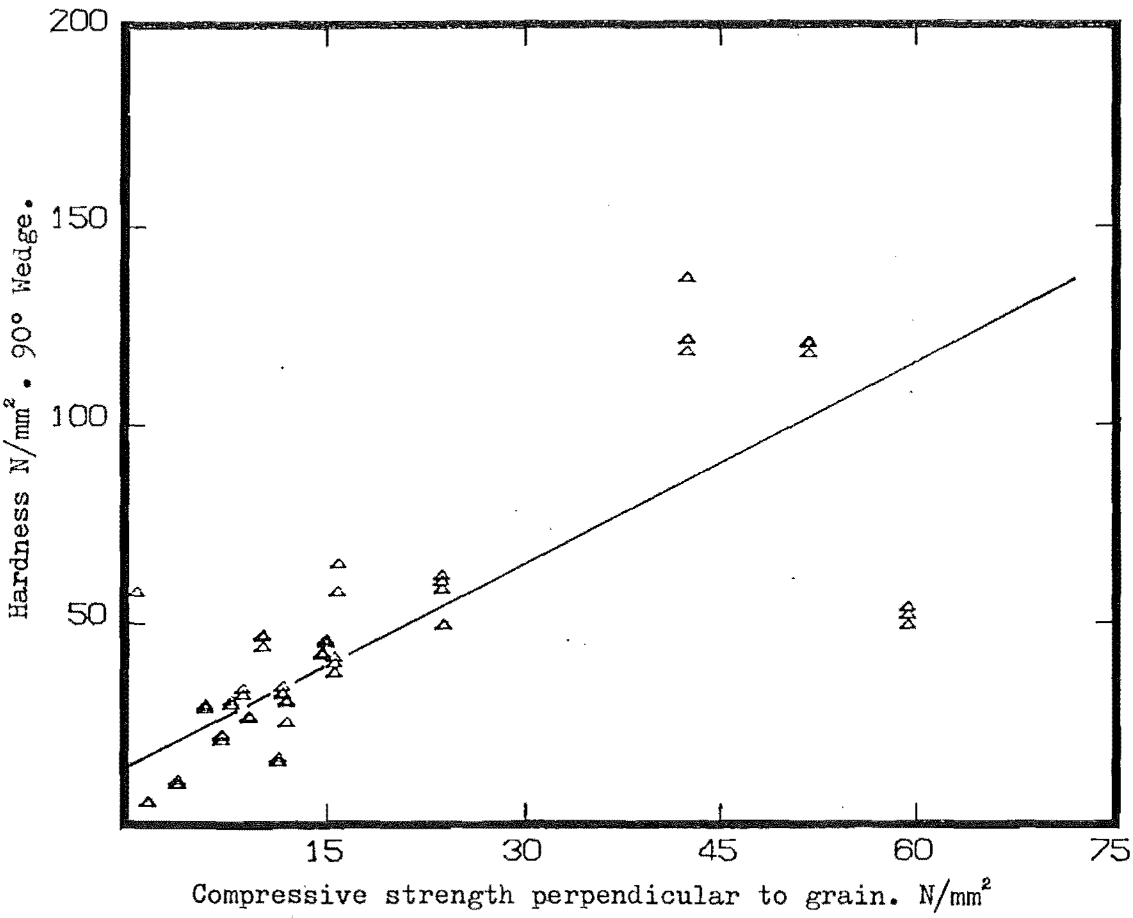
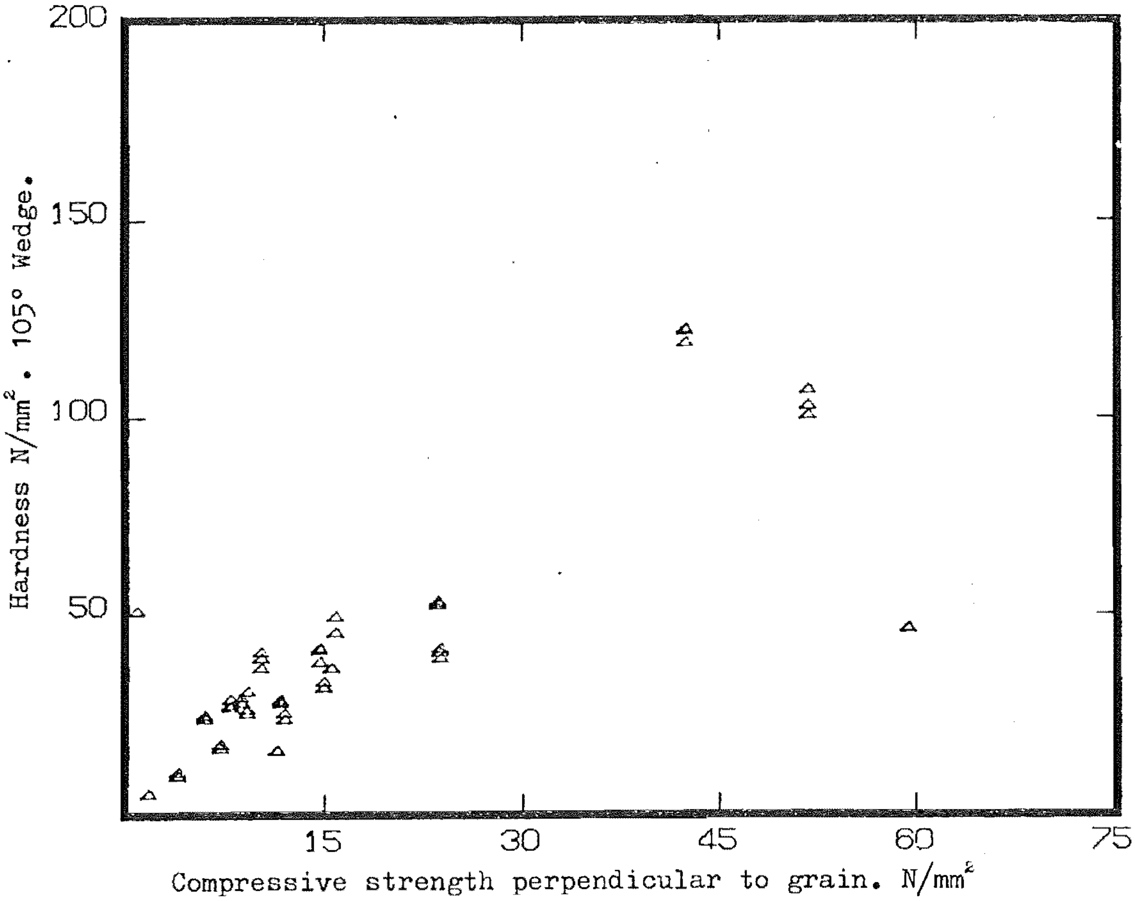


Fig. 29 - (a) and (b) Wedge Hardness versus Compressive strength perpendicular to the grain. 12% Moisture Content.



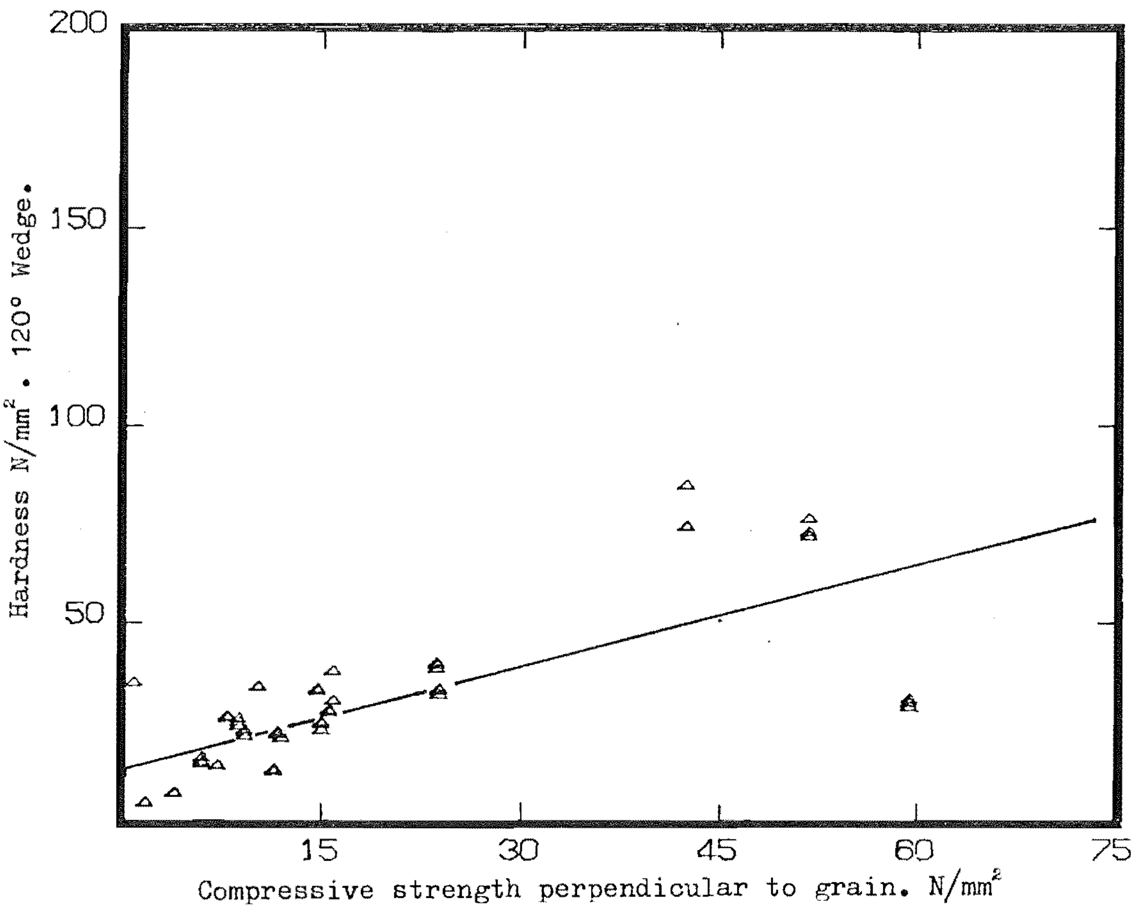
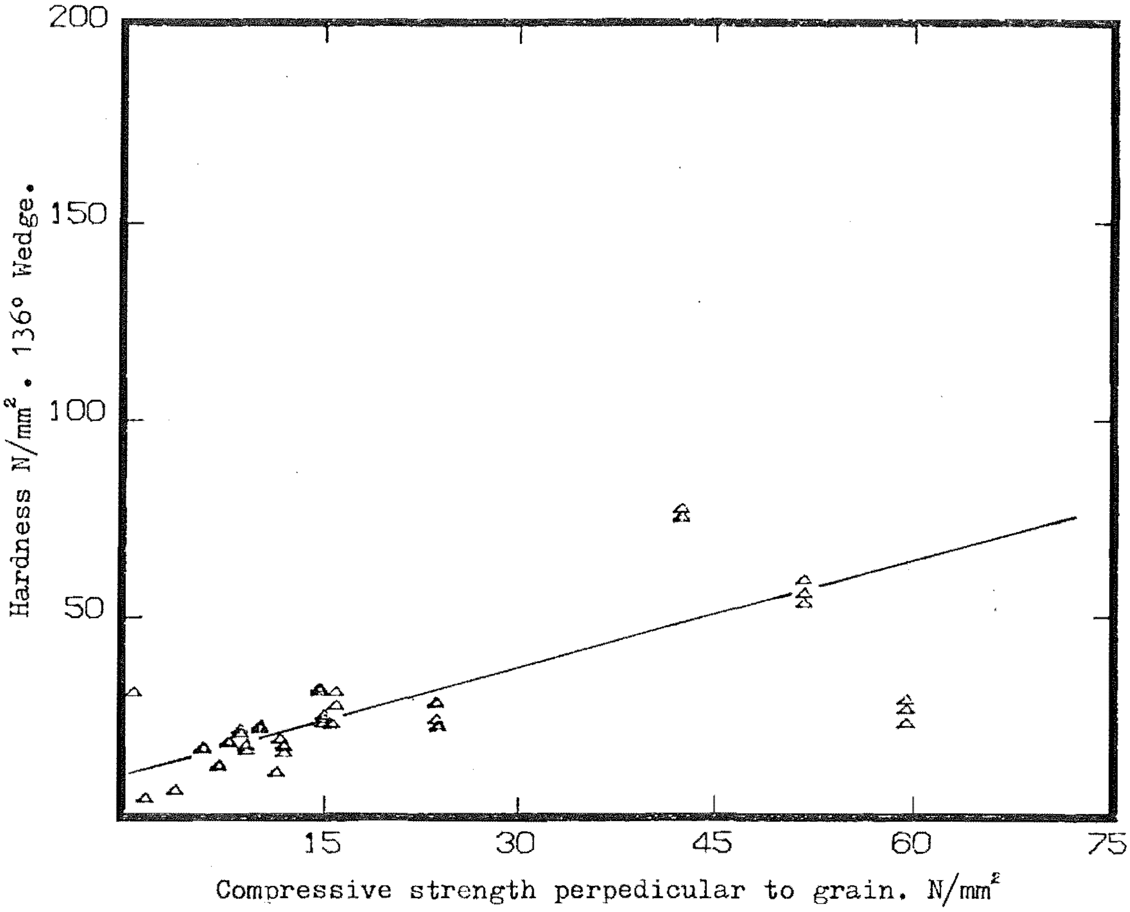


Fig. 29 - (c) and (d) Wedge Hardness versus Compressive strength perpendicular to the grain. 12% Moisture Content.



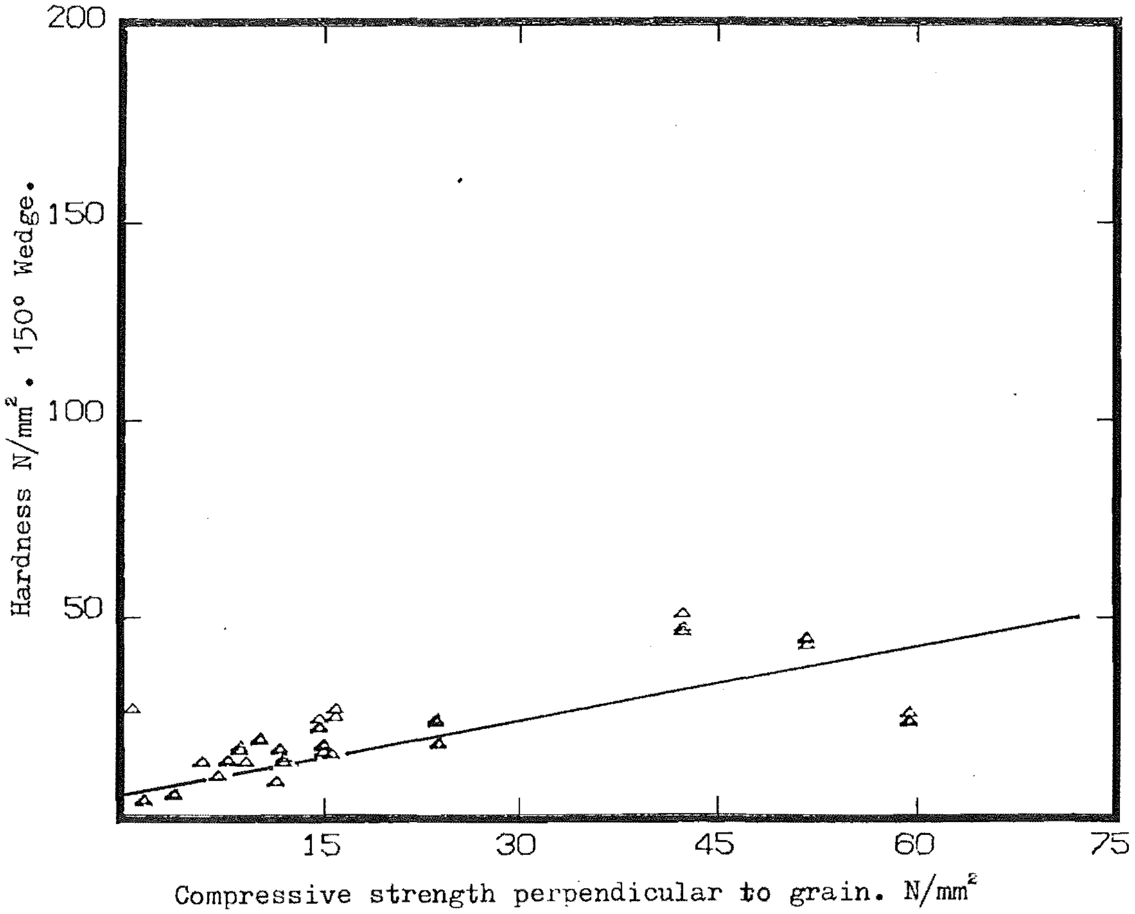
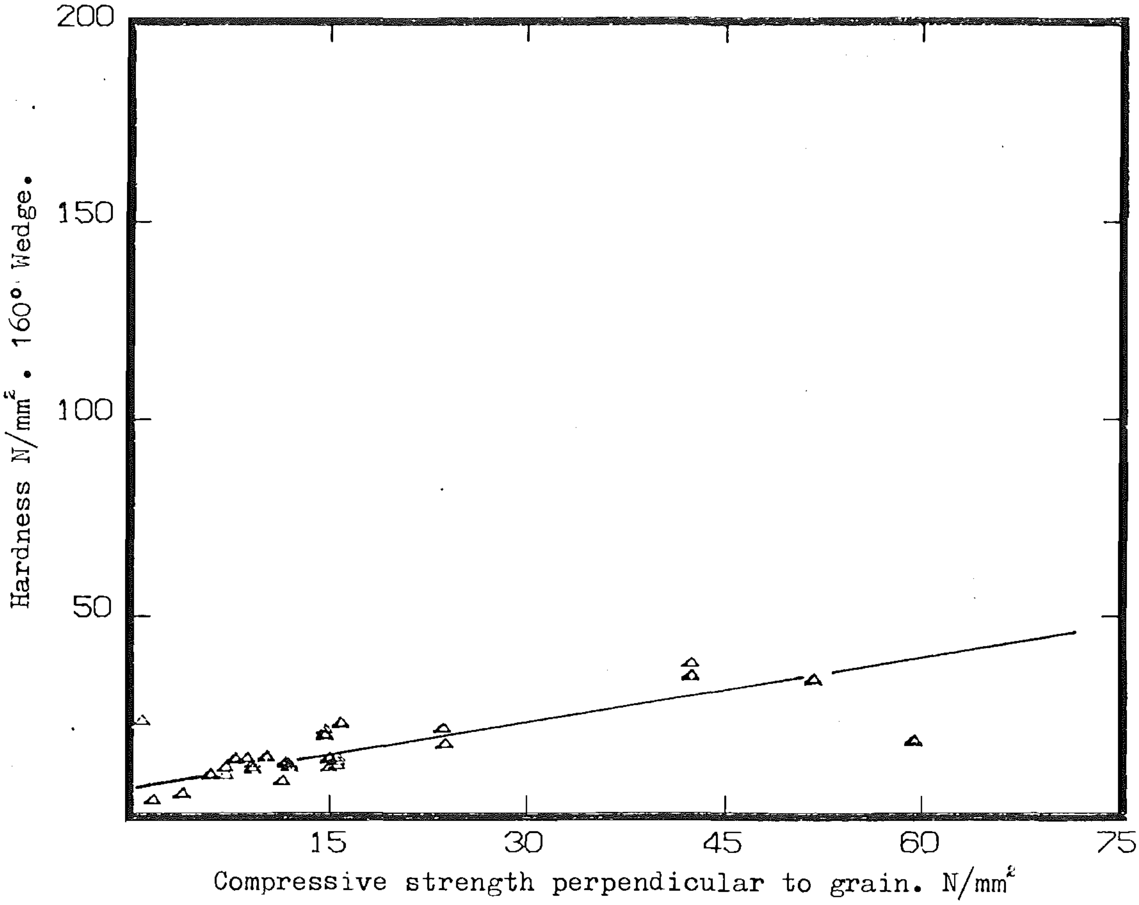


Fig. 29 - (e) and (f) Wedge Hardness versus Compressive strength perpendicular to the grain. 12% Moisture Content.



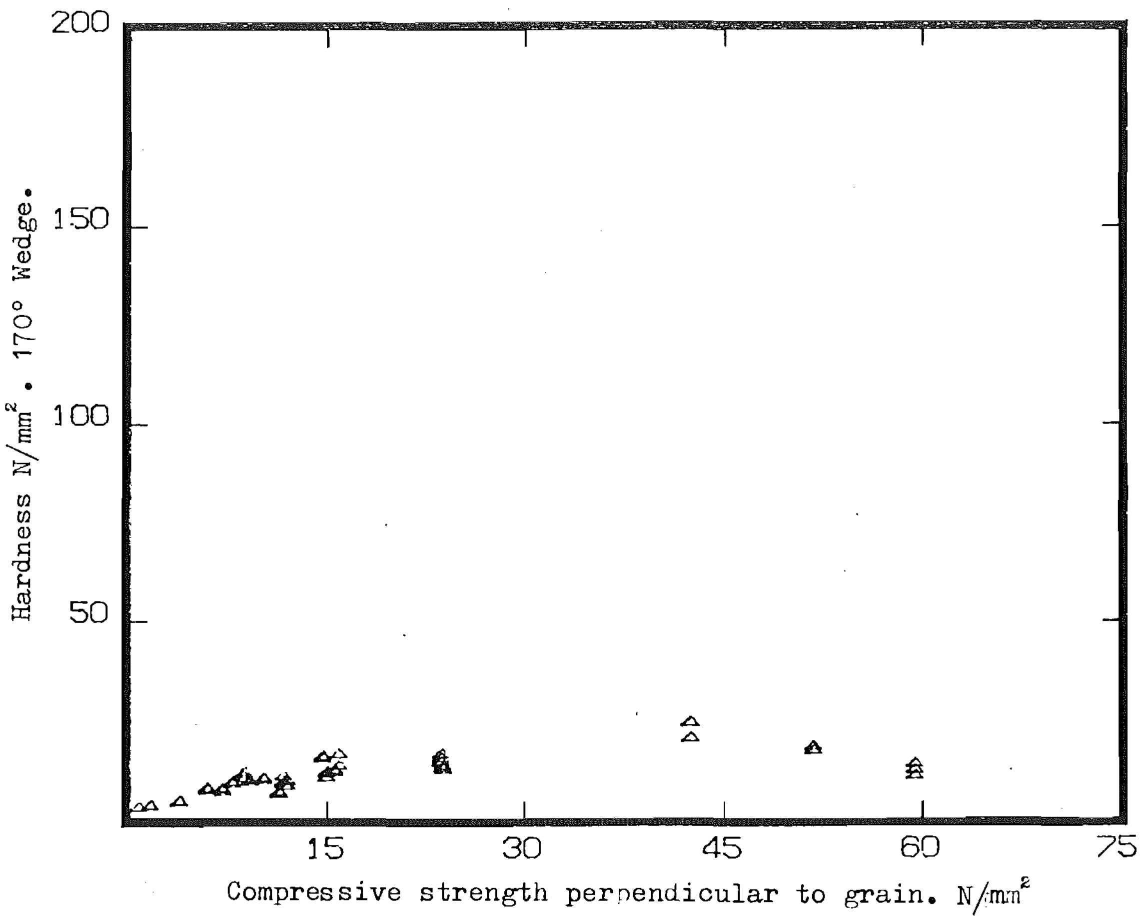


Fig. 29 - (g) and (h) Wedge Hardness versus Compressive strength perpendicular to the grain. 12% Moisture Content.

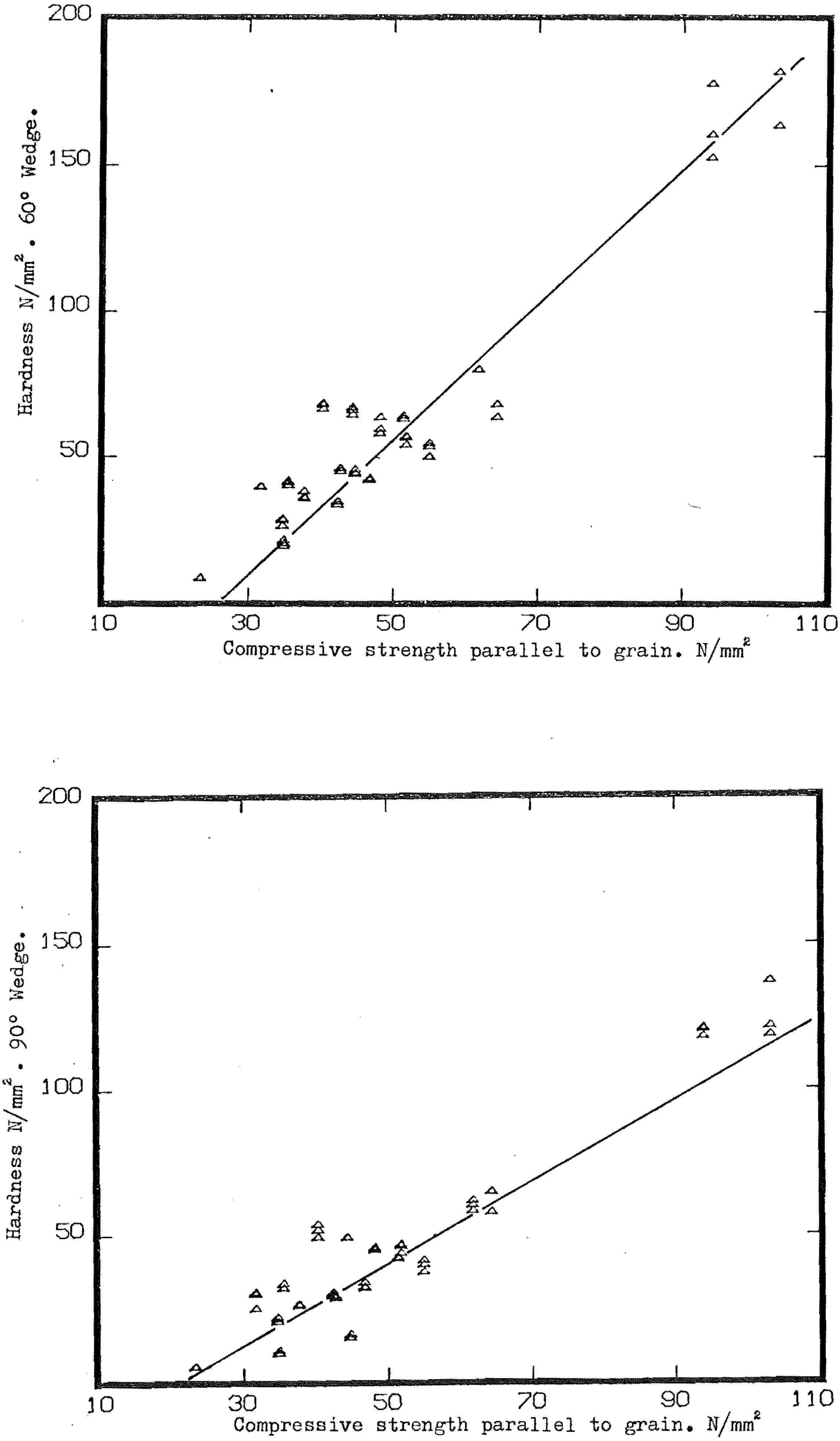


Fig. 30 - (a) and (b) Wedge Hardness versus Compressive strength parallel to the grain. 12% Moisture Content.

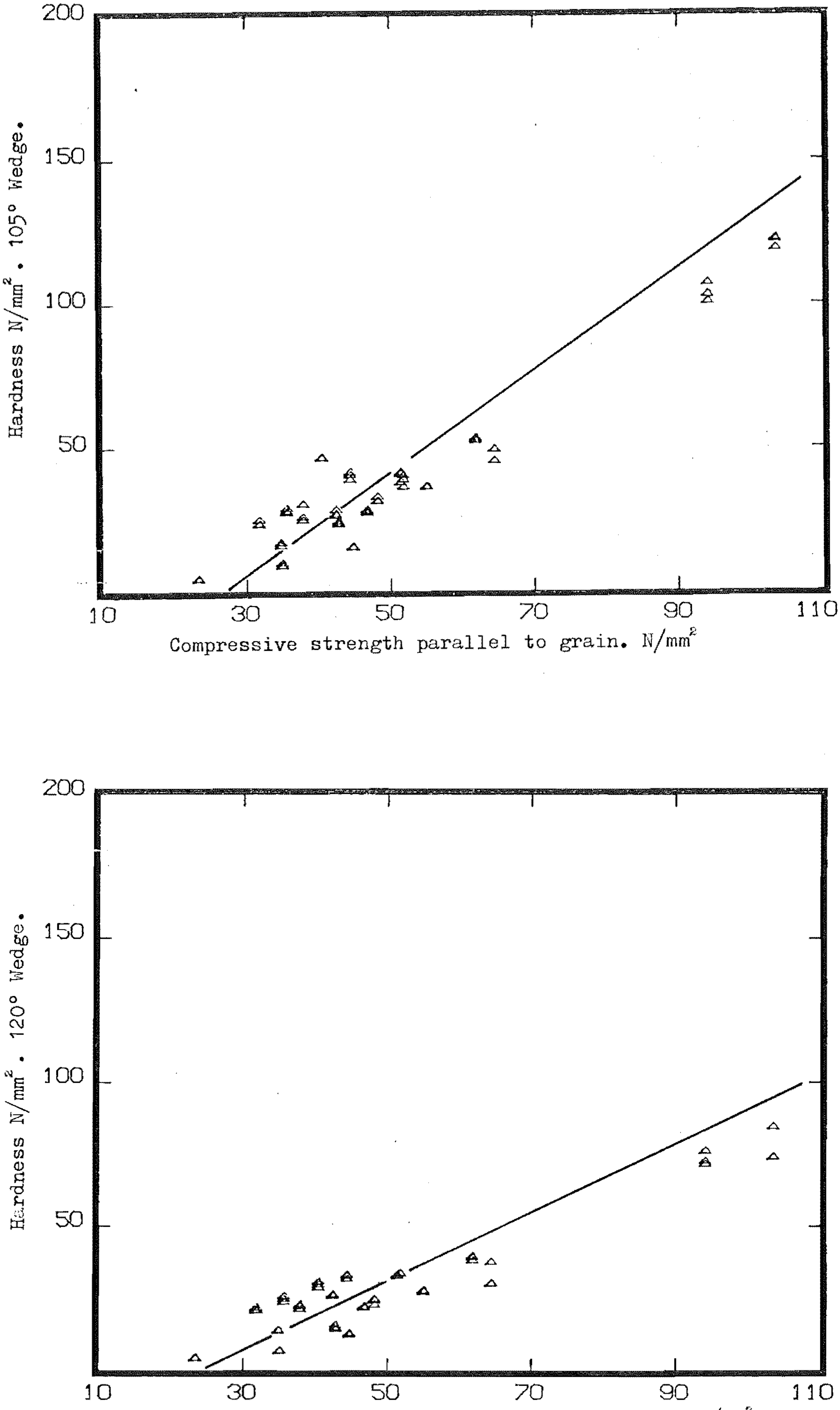
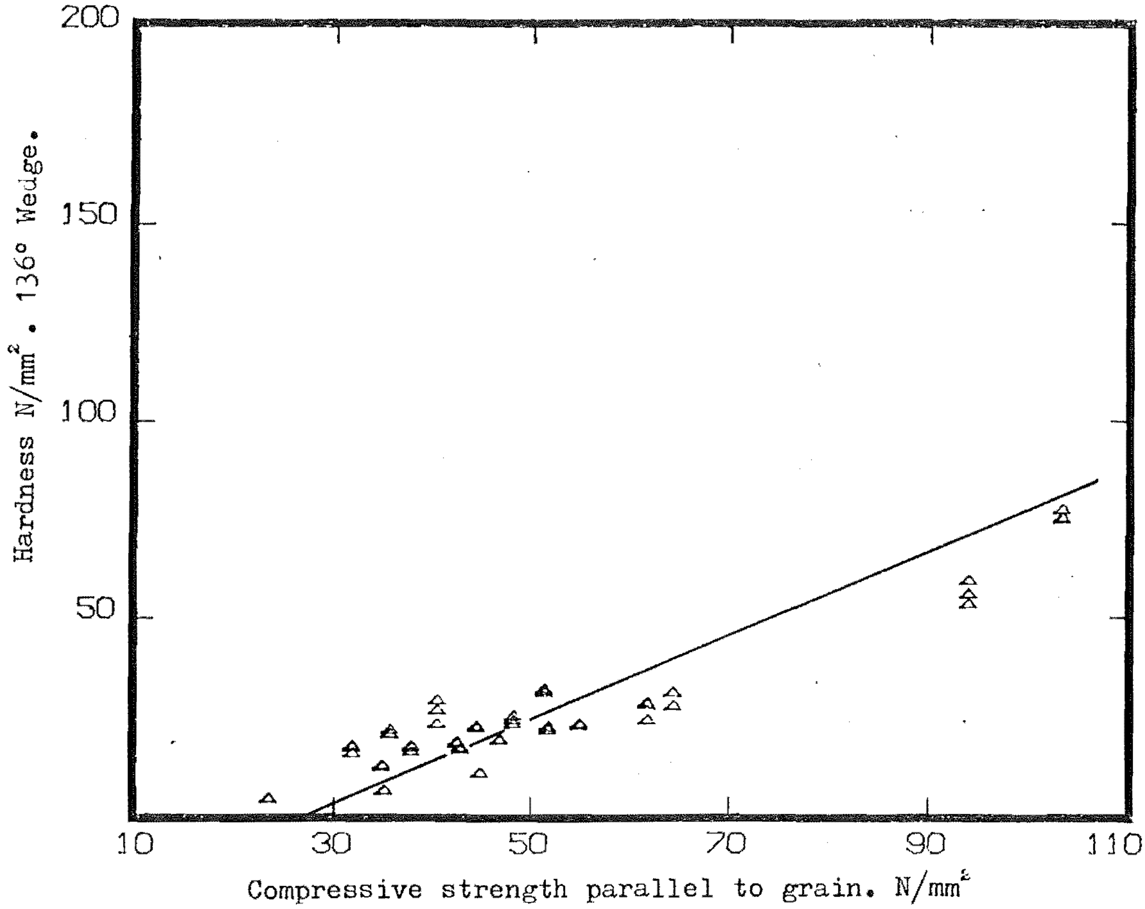


Fig. 30 - (c) and (d) Wedge Hardness versus Compressive strength parallel to the grain. 12% Moisture Content.



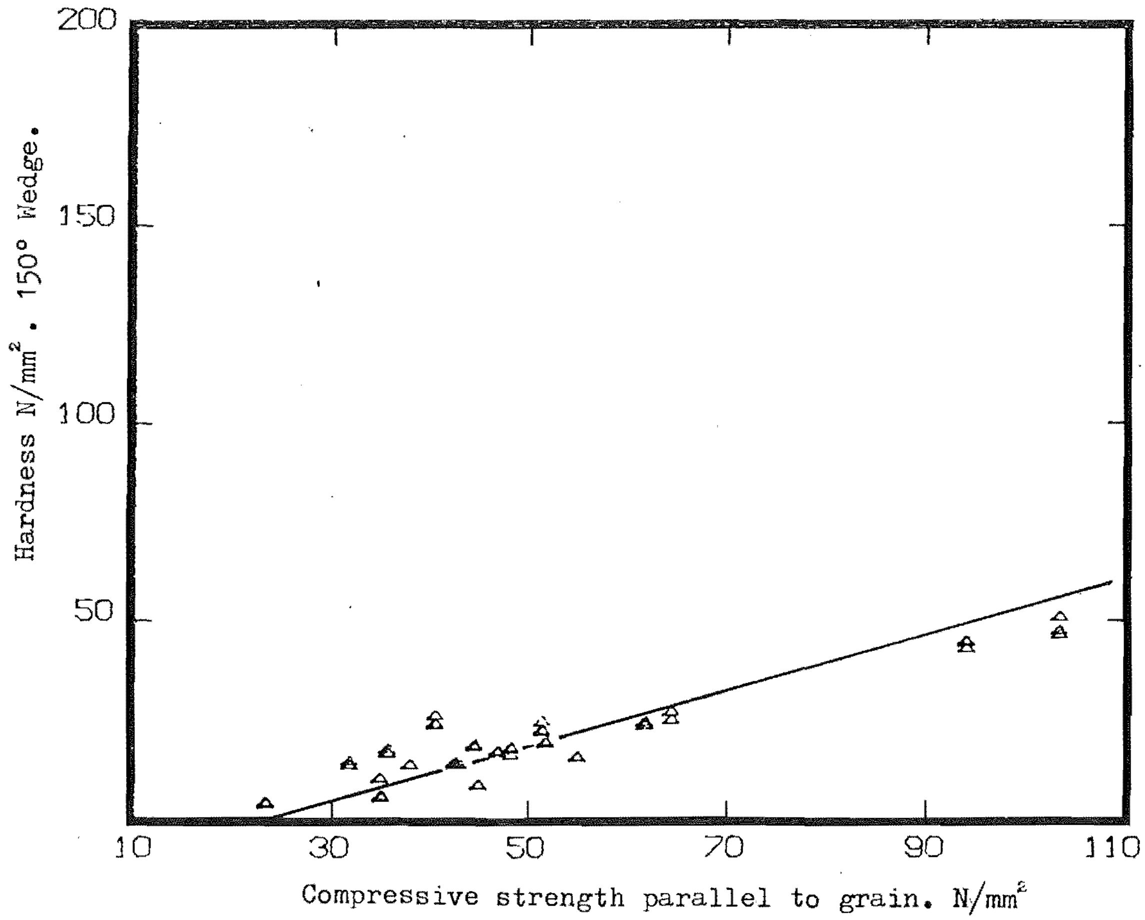
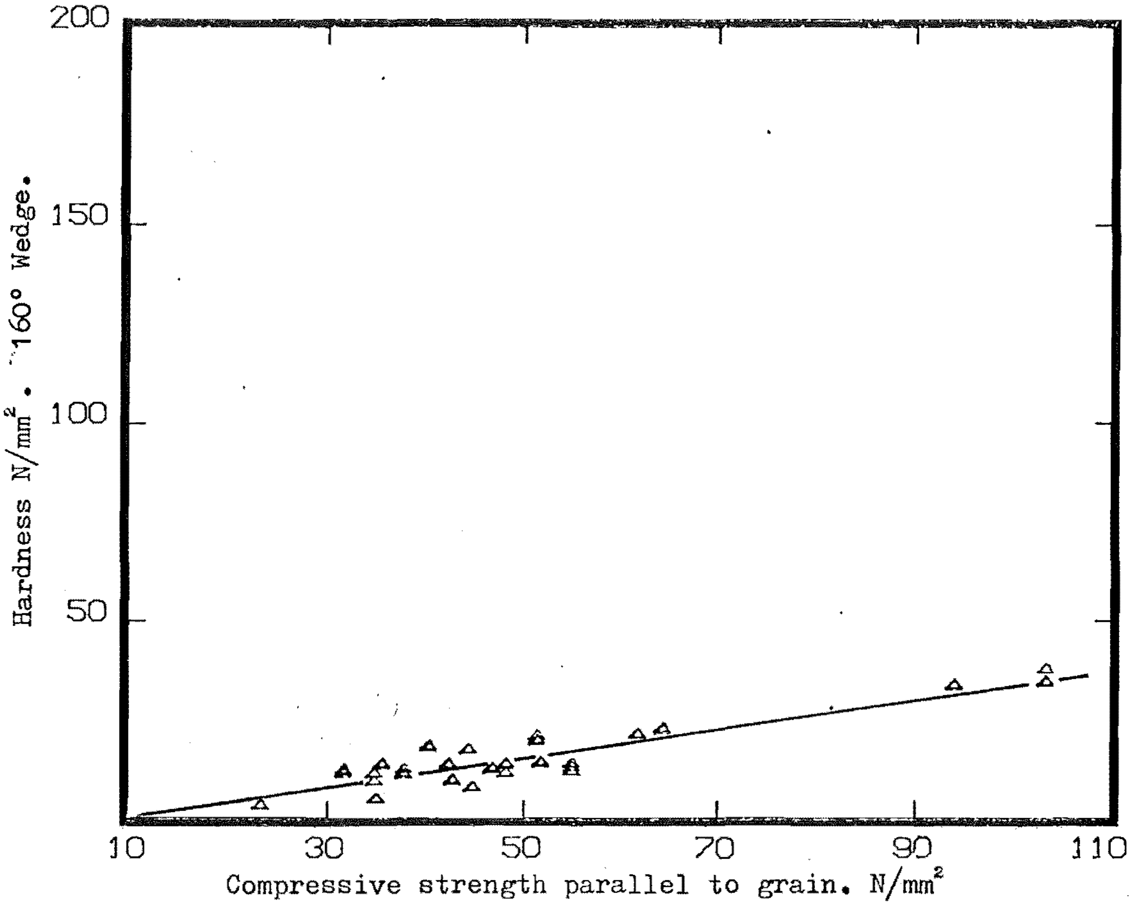


Fig. 30 - (e) and (f) Wedge Hardness versus Compressive strength parallel to the grain. 12% Moisture Content.



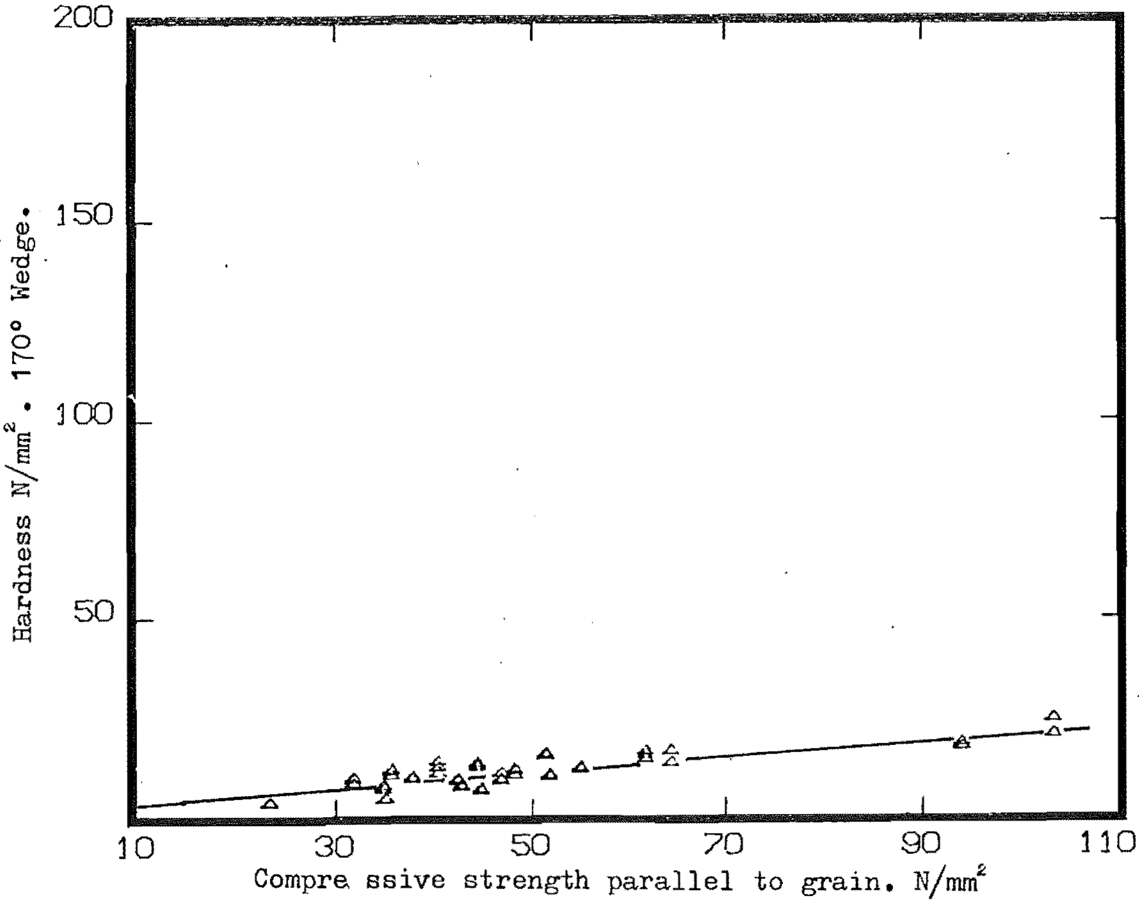
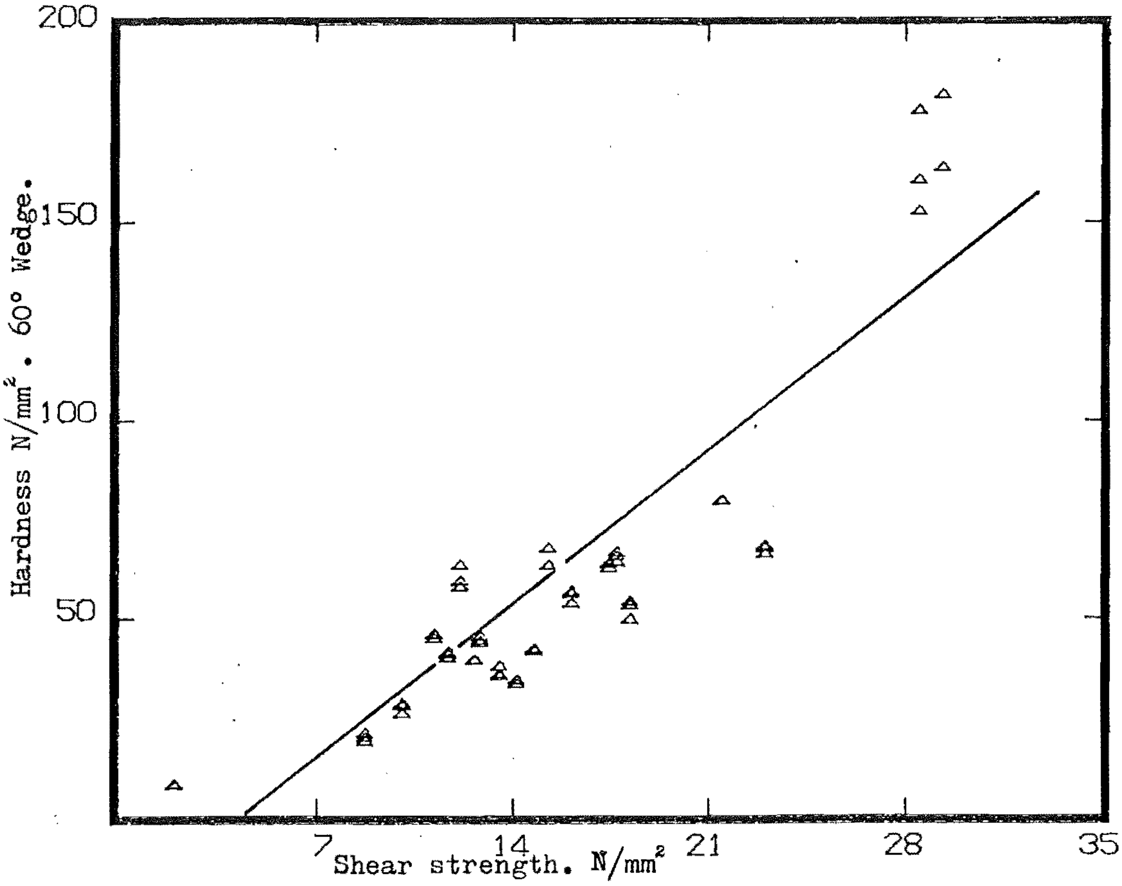


Fig. 30 - (g) and (h) Wedge Hardness versus Compressive strength parallel to the grain. 12% Moisture Content.



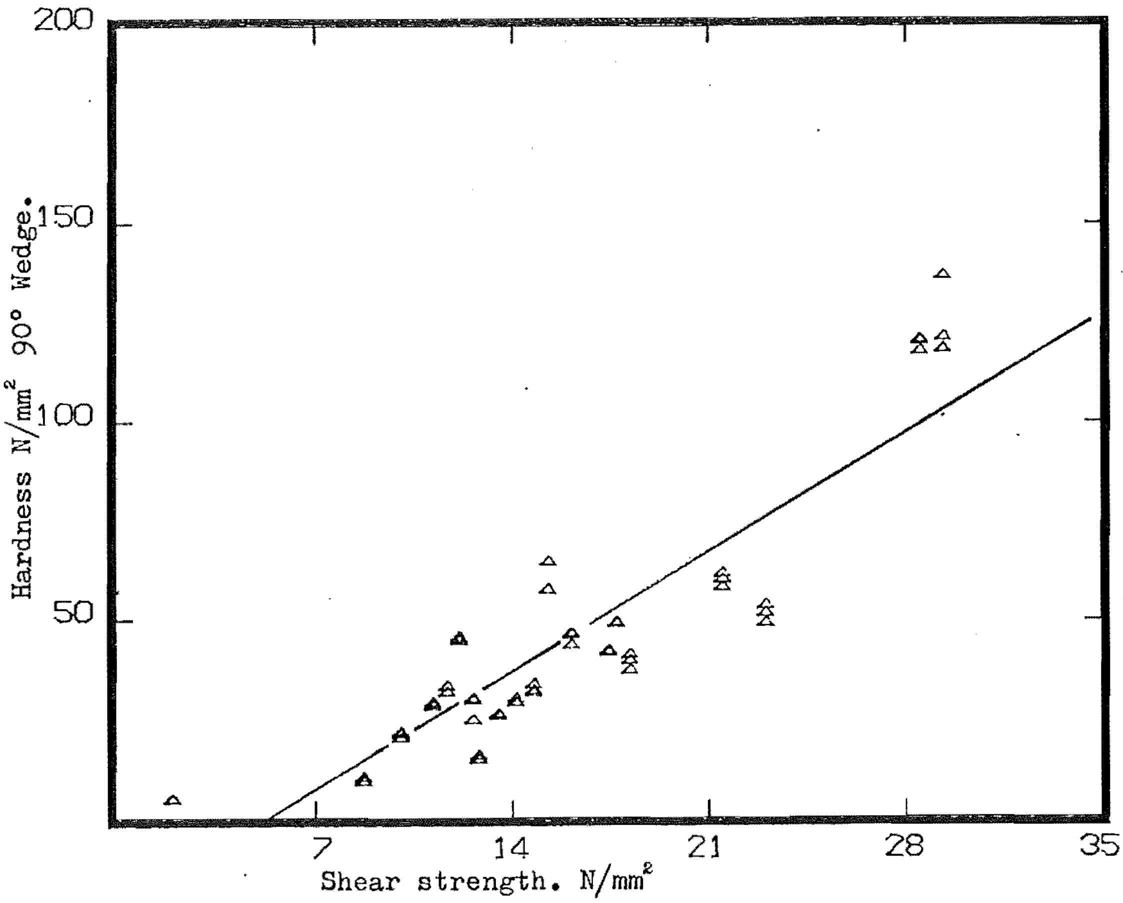
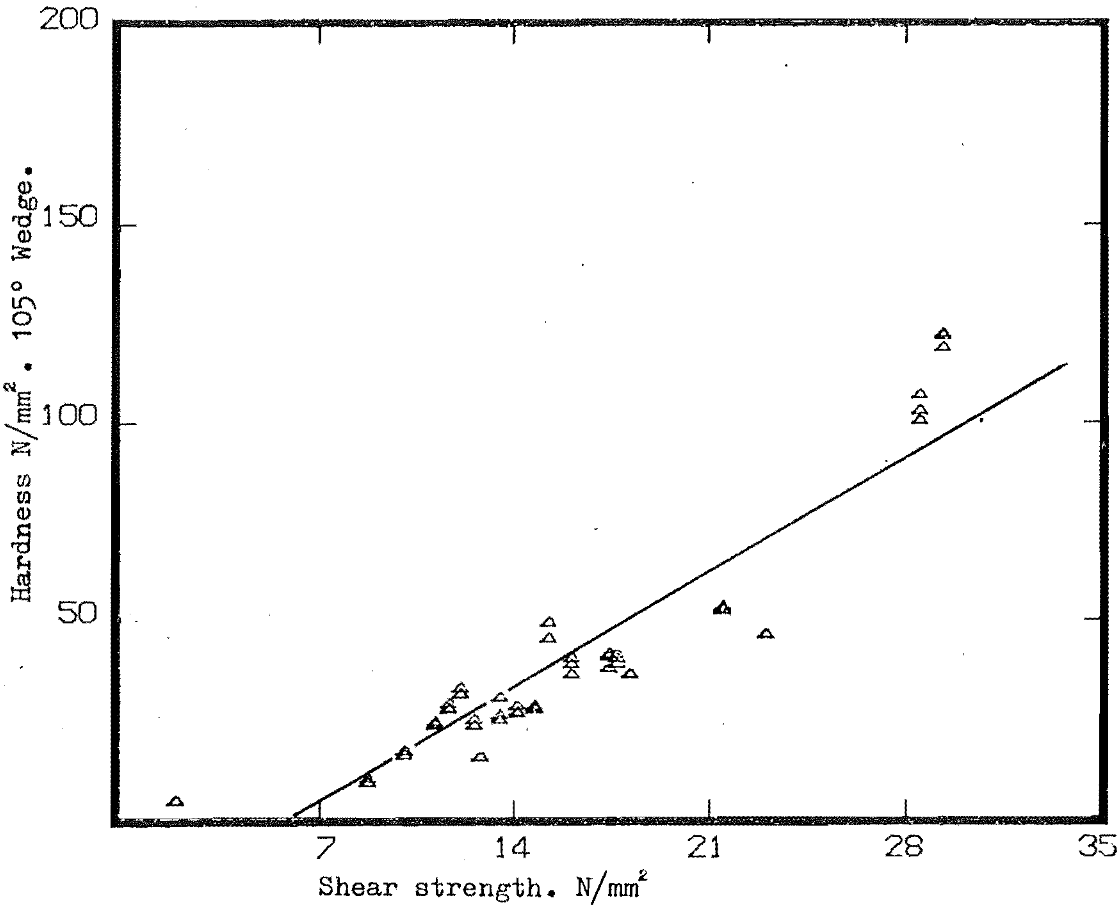


Fig. 31 - (a) and (b) Wedge Hardness versus Shear Strength. 12% Moisture Content.



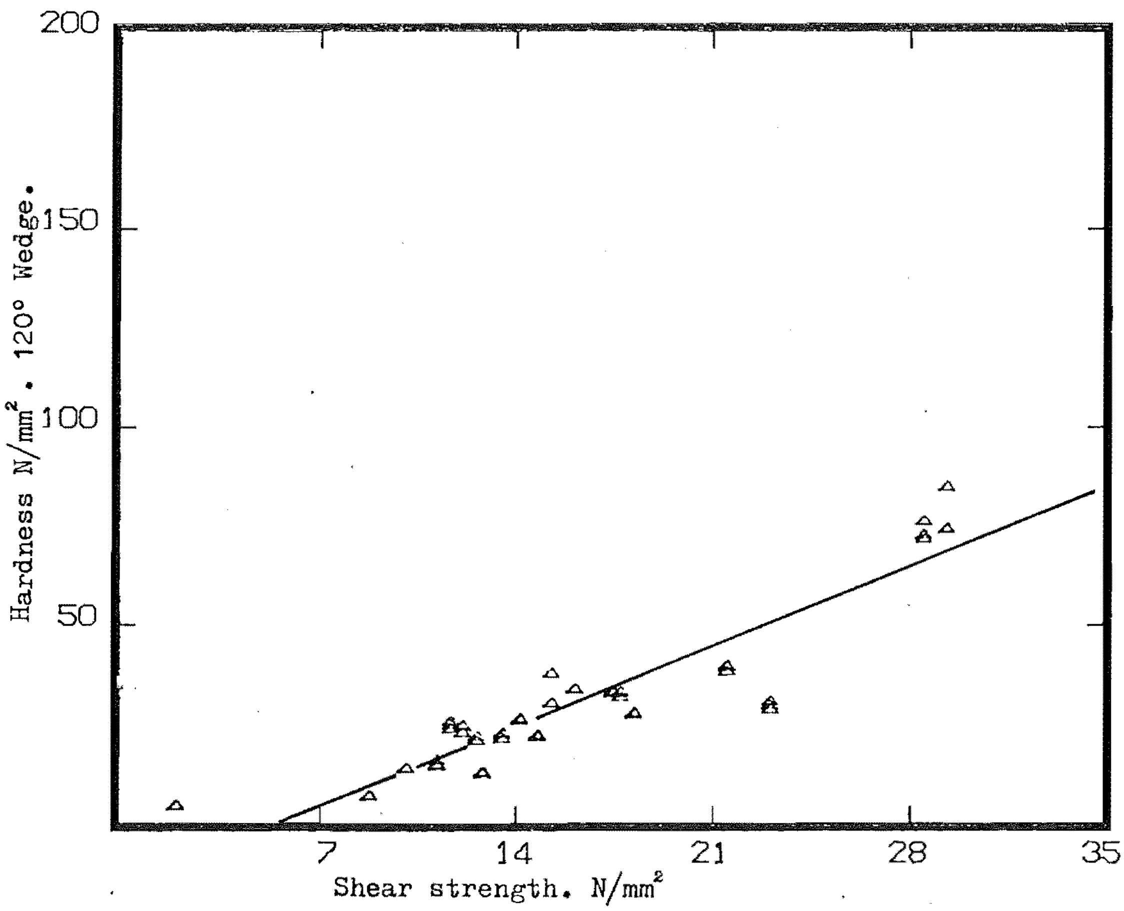
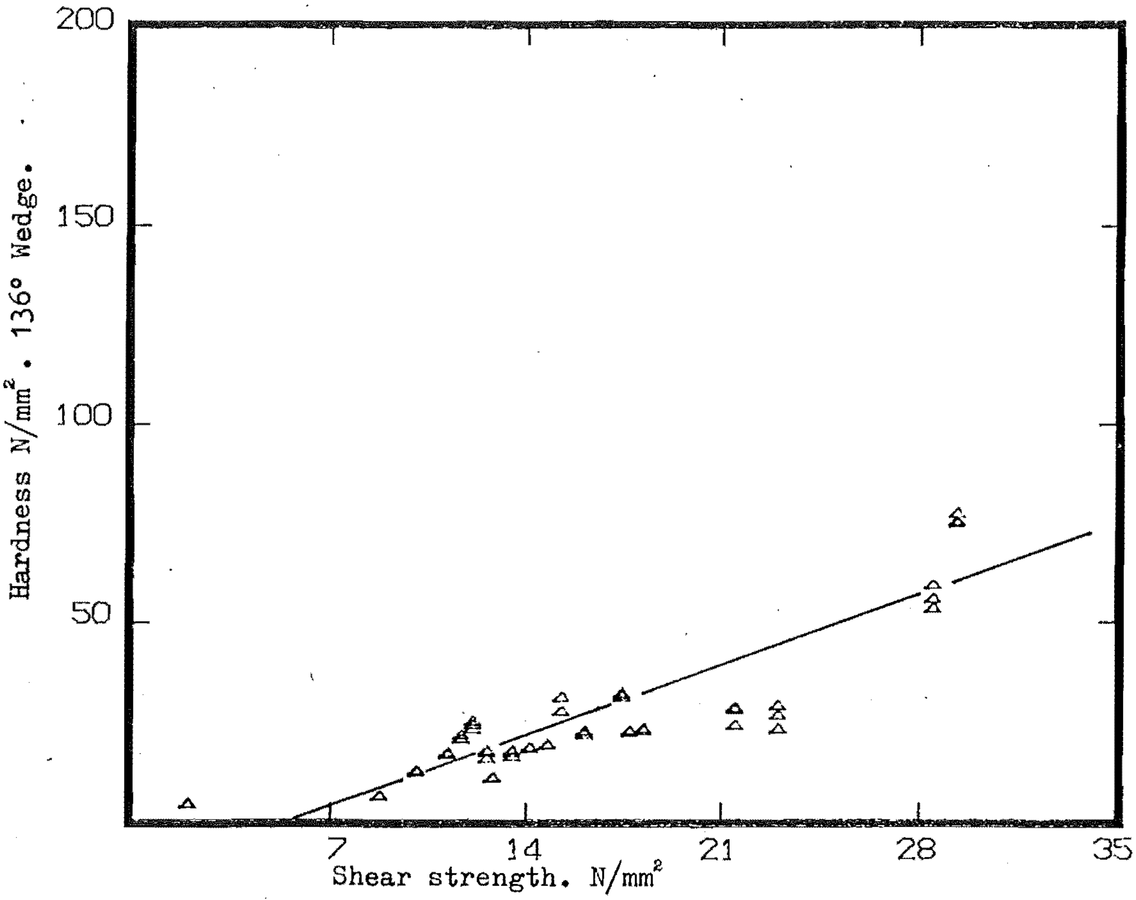


Fig. 31 - (c) and (d) Wedge Hardness versus Shear Strength.
12% Moisture Content.



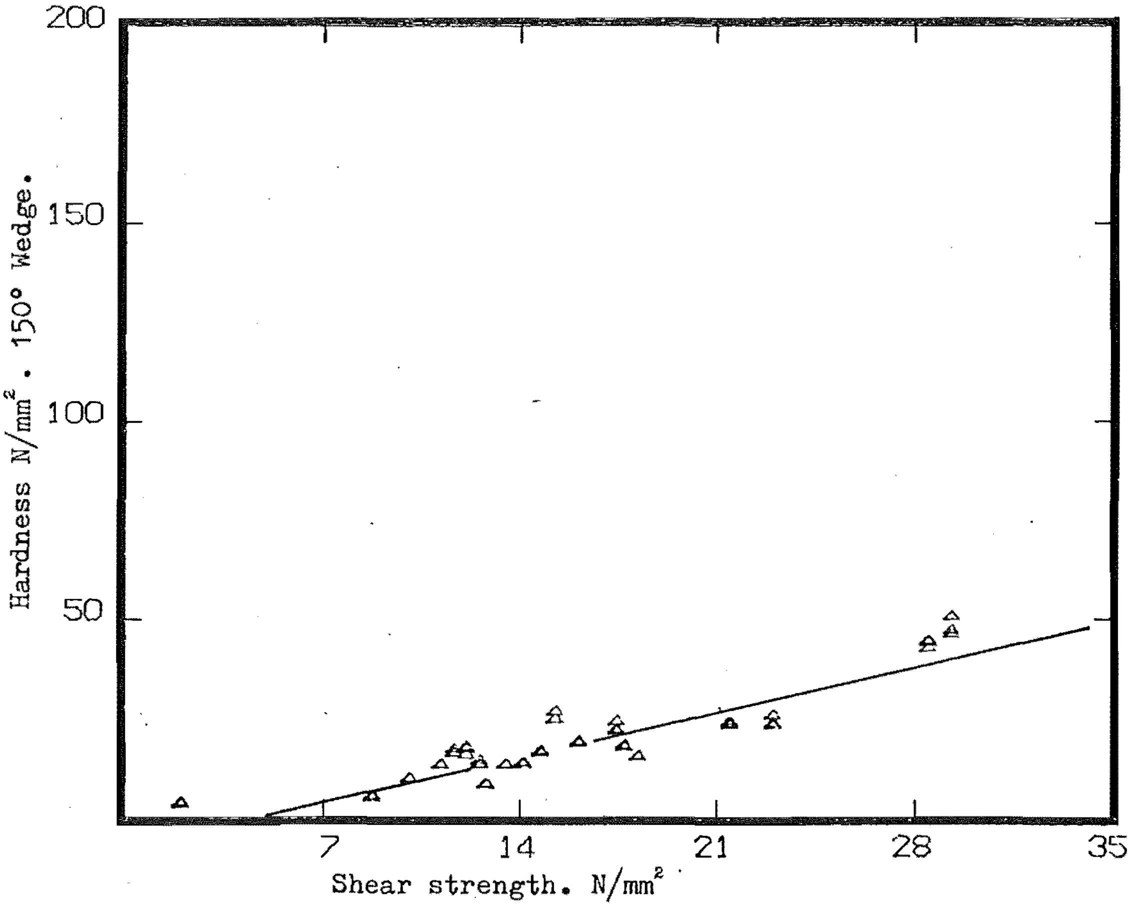
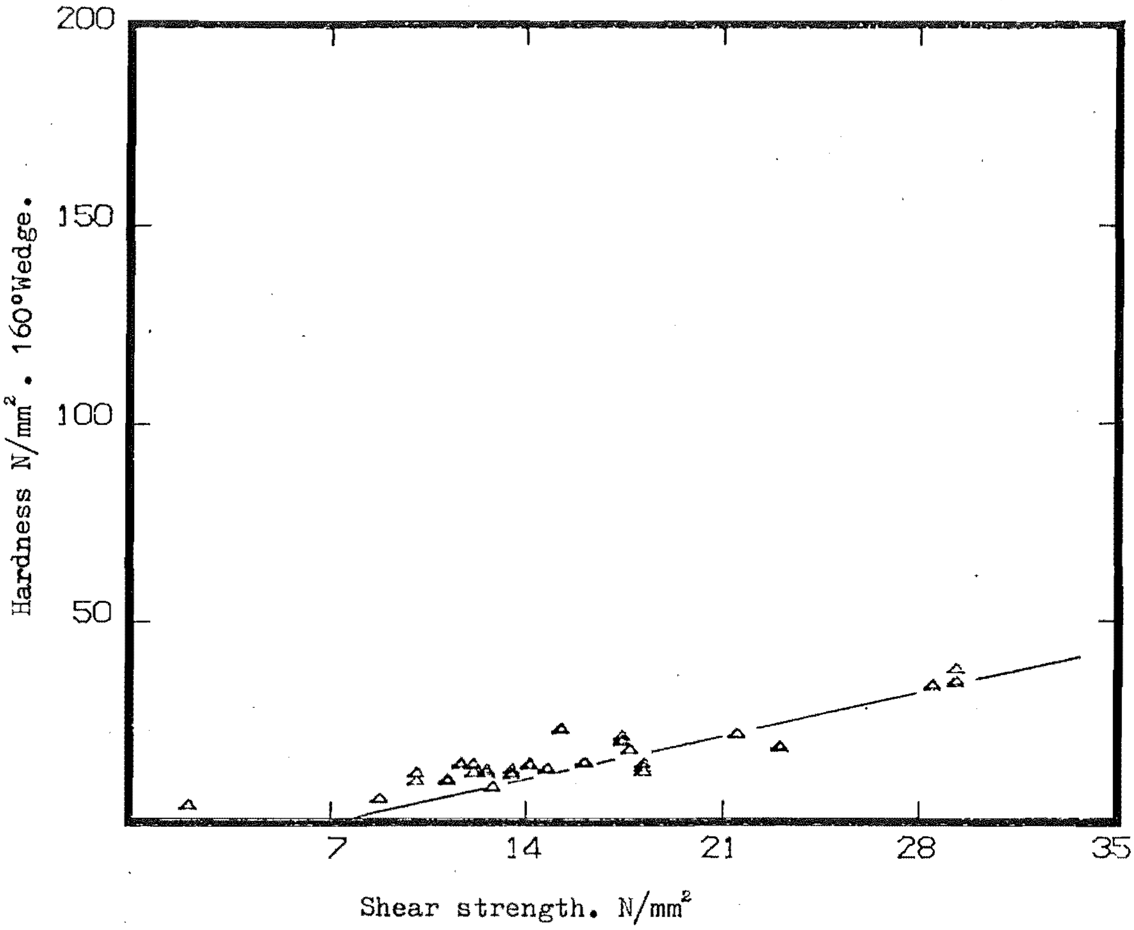


Fig. 31 - (e) and (f) Wedge Hardness versus Shear Strength. 12% Moisture Content.



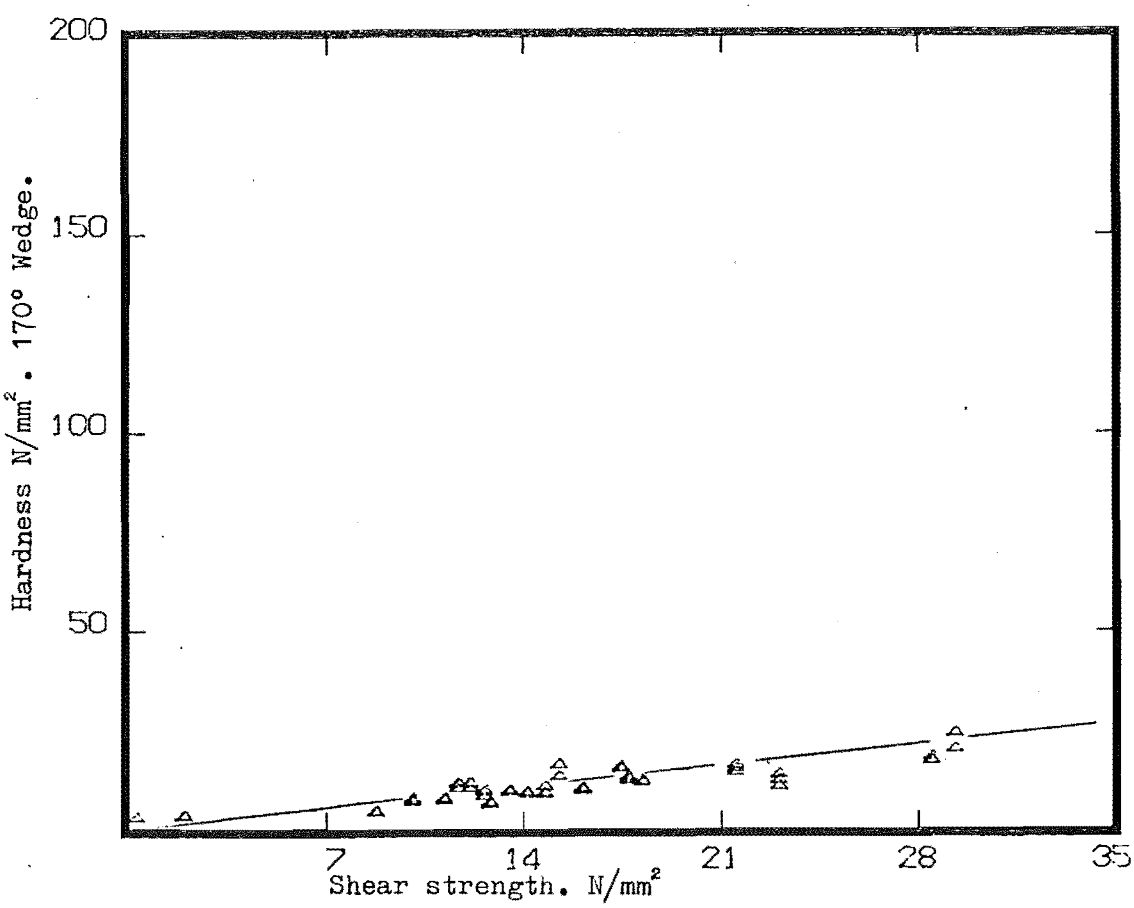
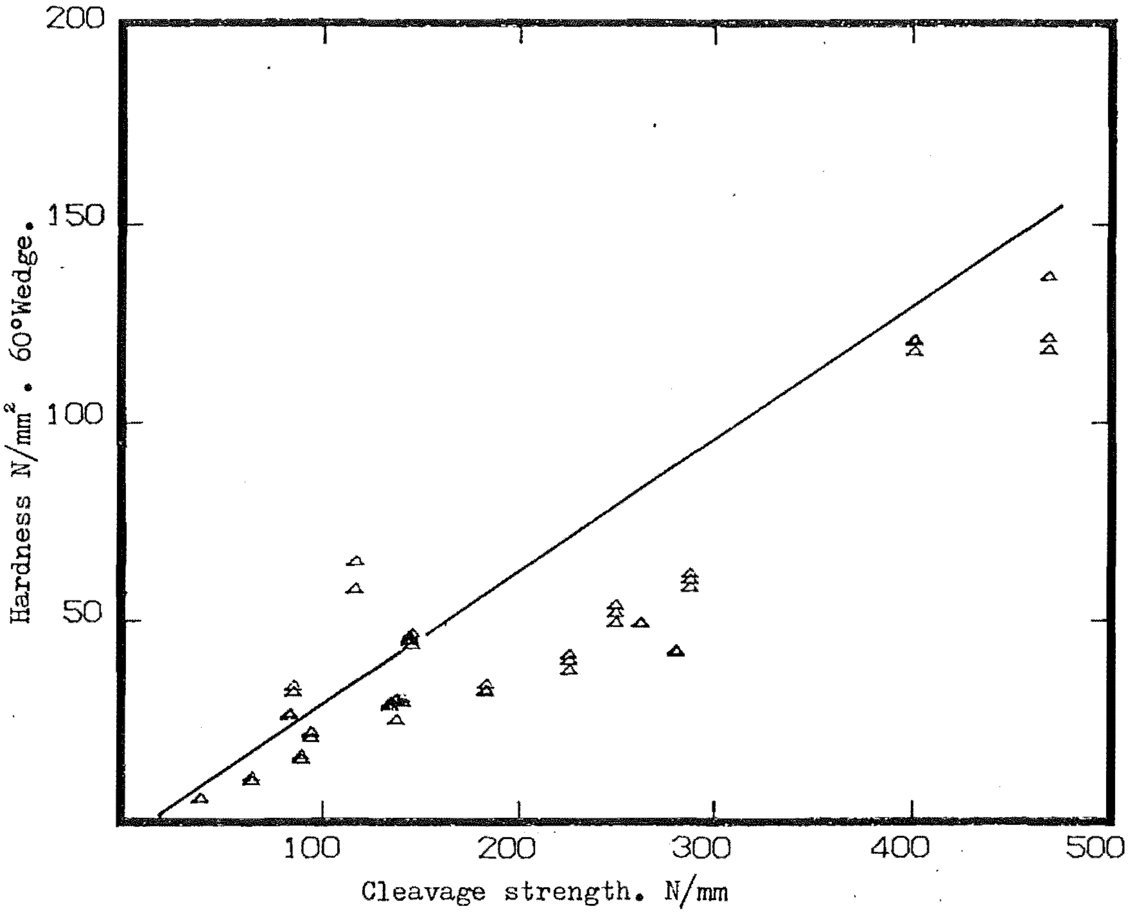


Fig. 31 - (g) and (h) Wedge Hardness versus Shear Strength. 12% Moisture Content.



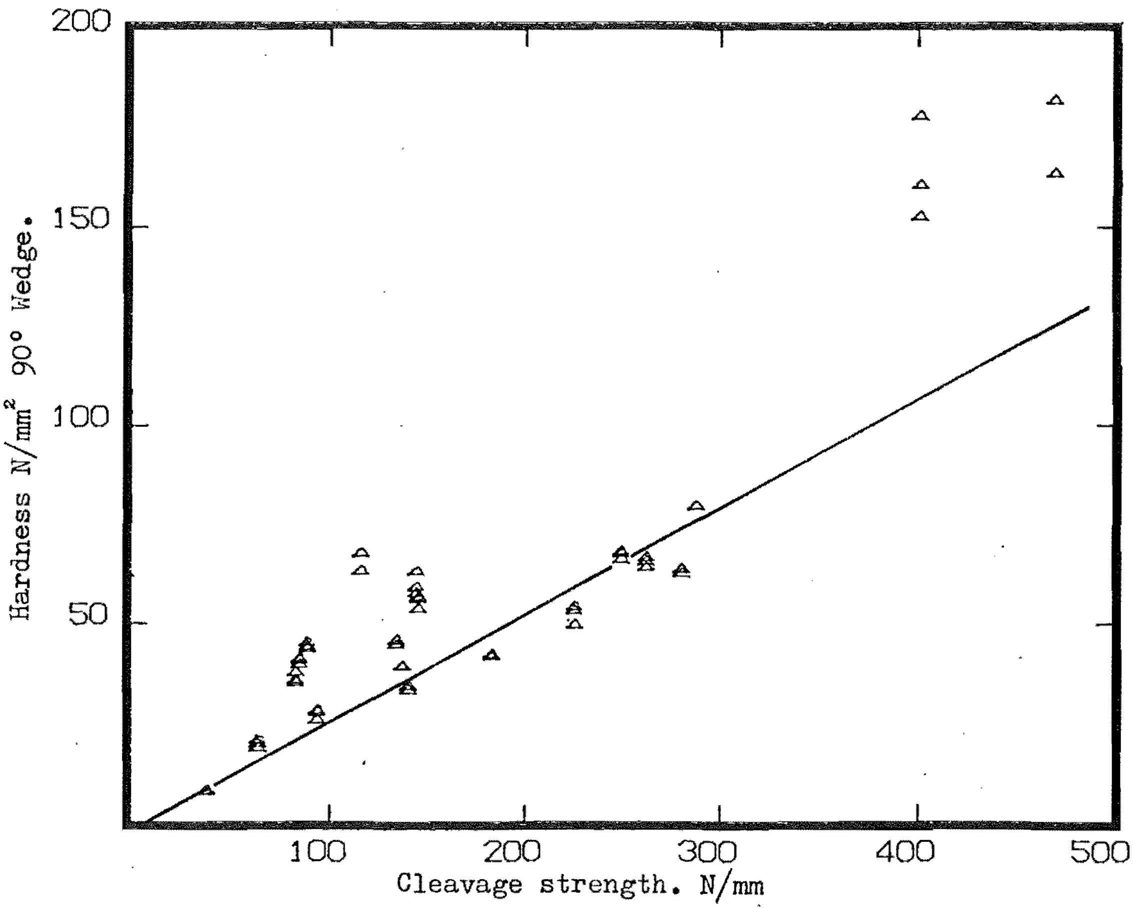
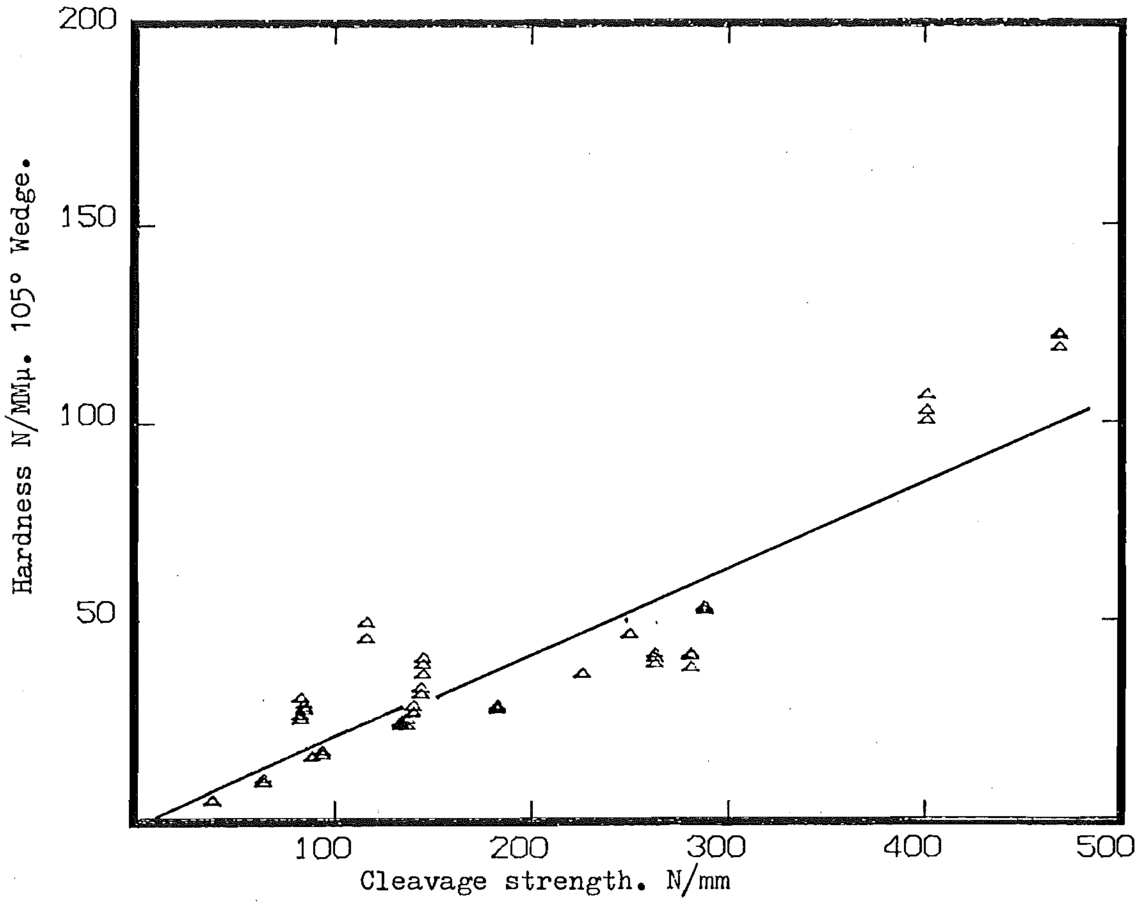


Fig. 32 - (a) and (b) Wedge Hardness versus Cleavage Strength. 12% Moisture Content.



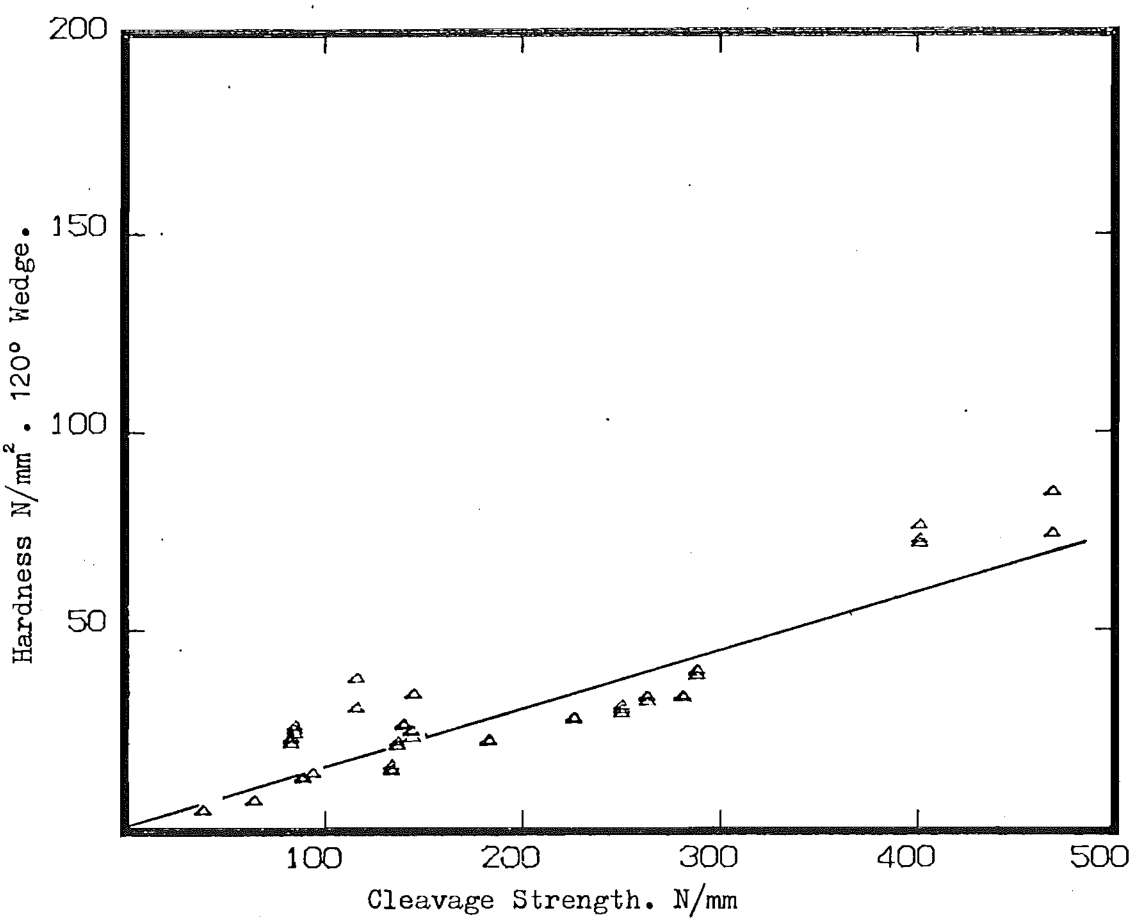
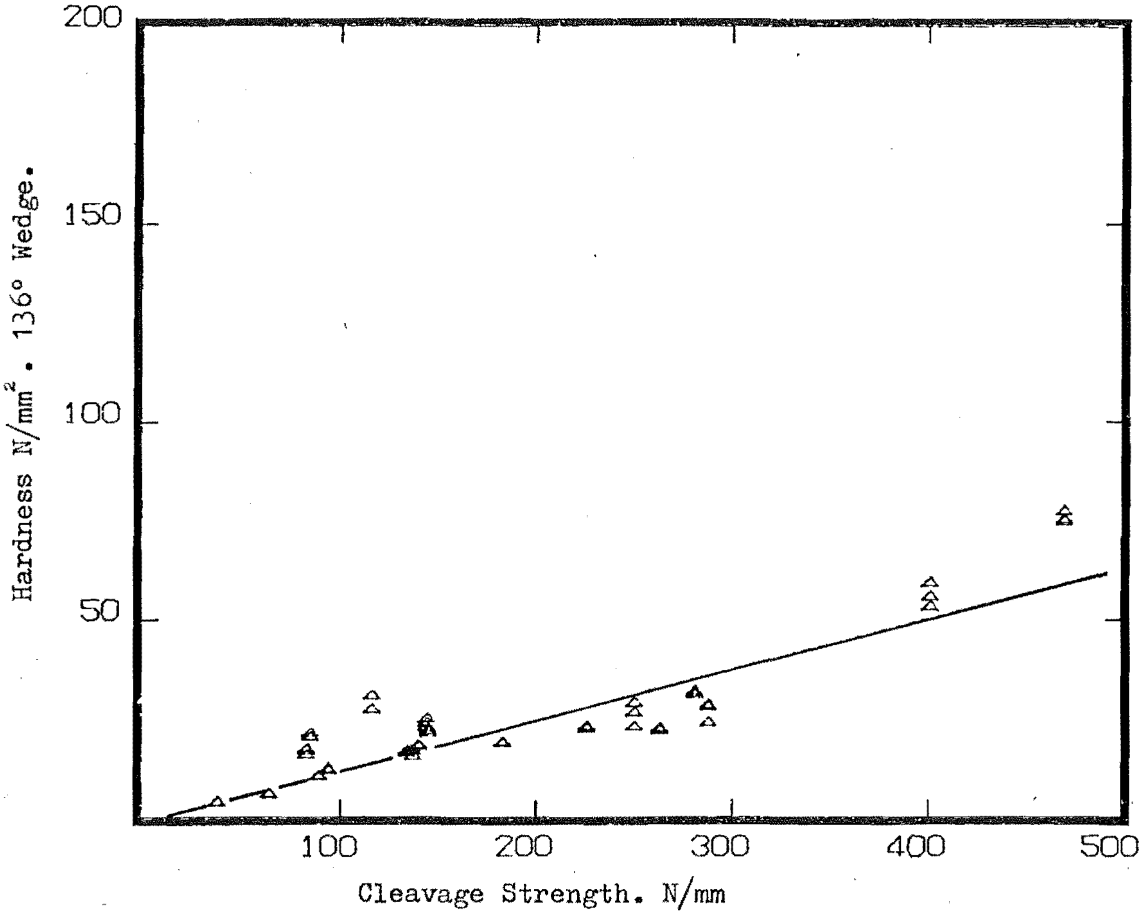


Fig. 32 - (c) and (d) Wedge Hardness versus Cleavage Strength. 12% Moisture Content.



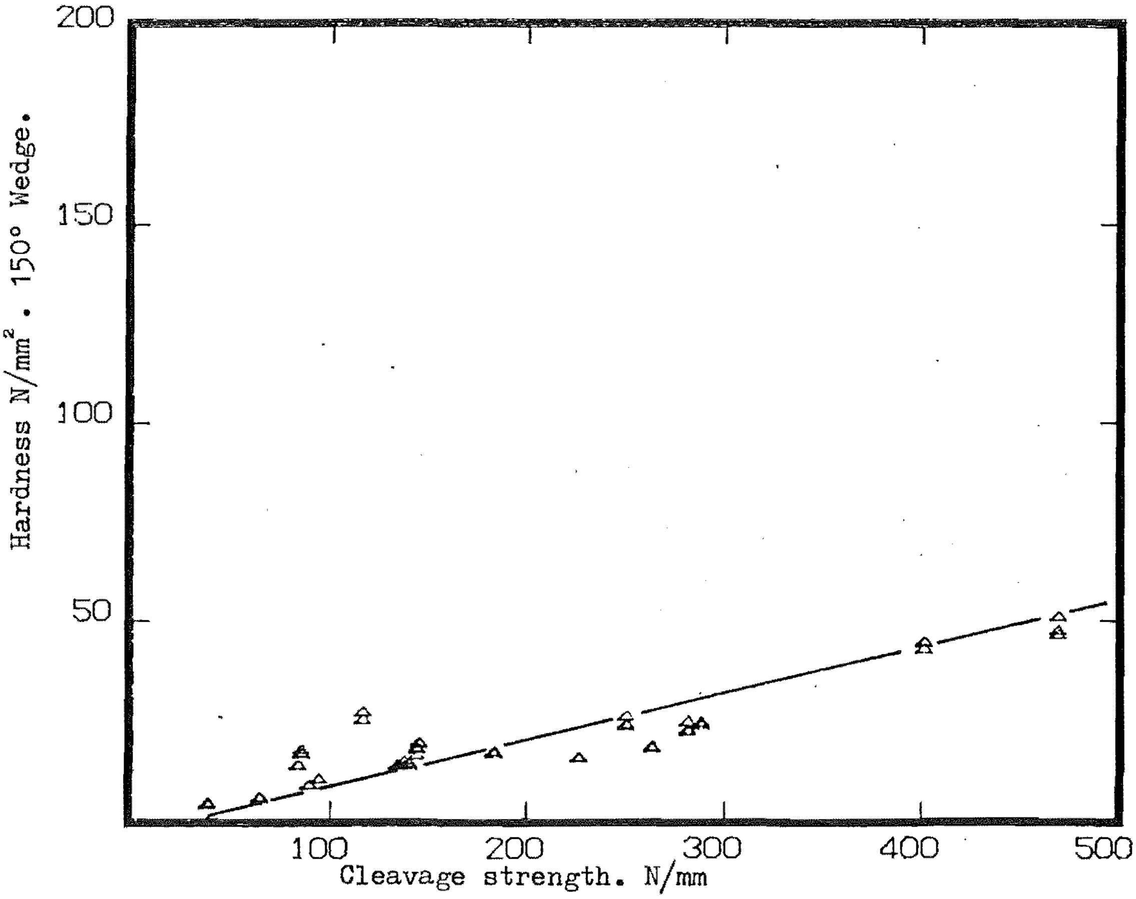
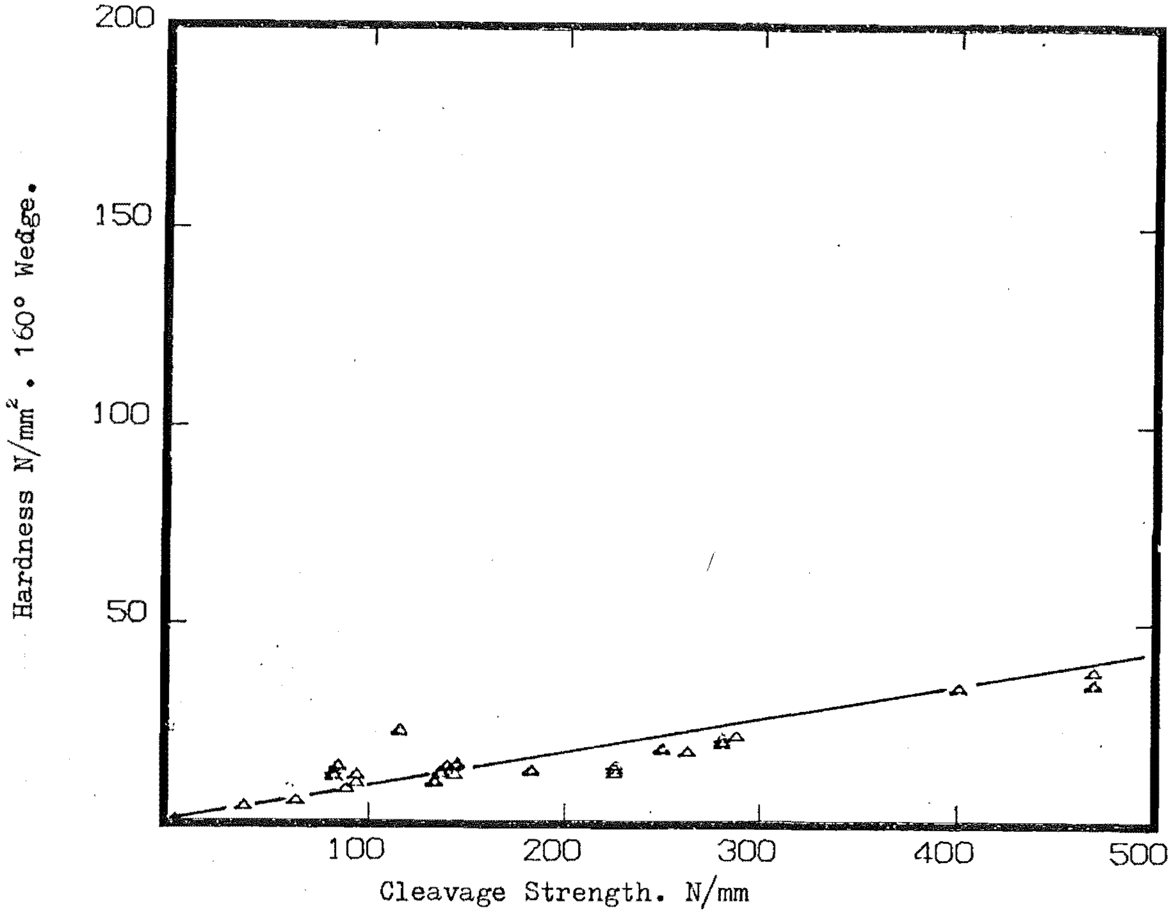


Fig. 32 - (e) and (f) Wedge Hardness versus Cleavage Strength. 12% Moisture Content.



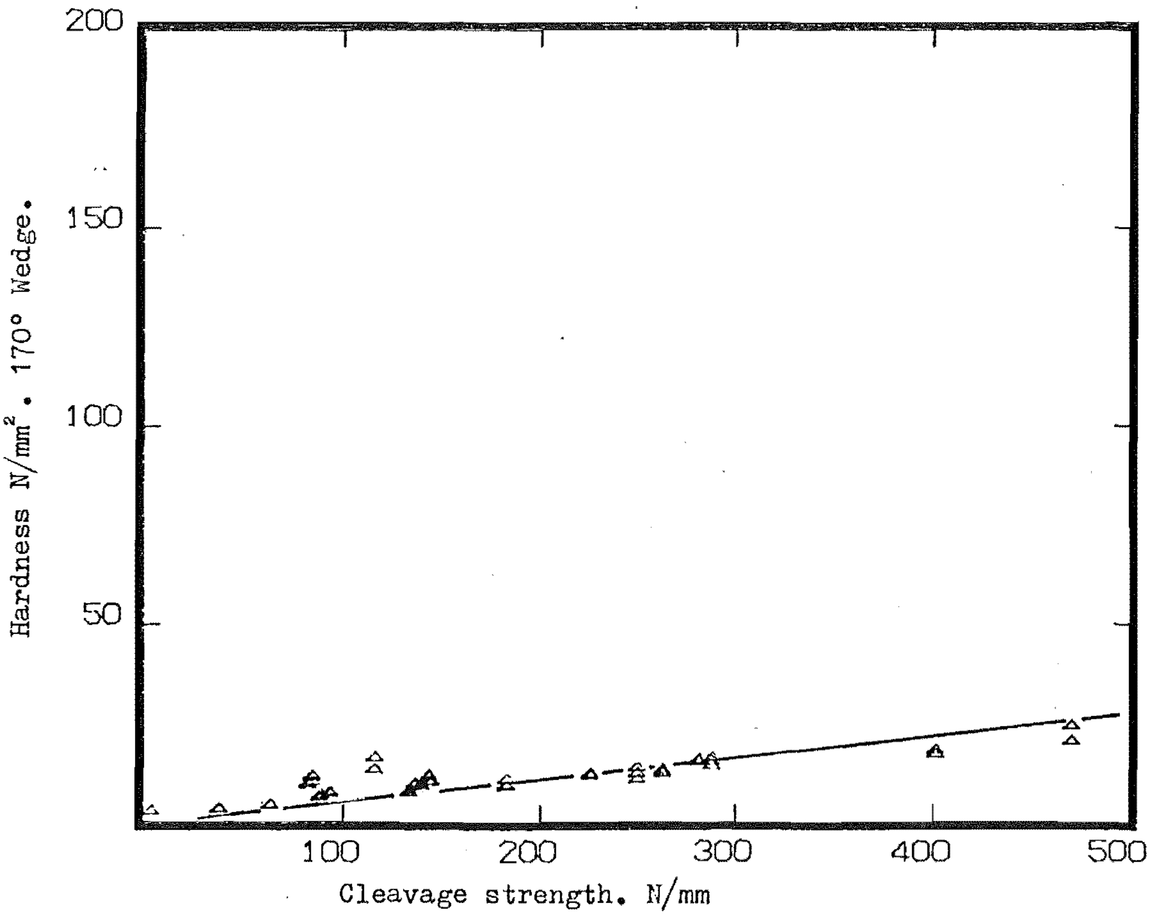


Fig. 32 - (g) and (h) Wedge Hardness versus Cleavage Strength. 12% Moisture Content.

5.3.4 THE EFFECT OF MOISTURE CONTENT ON STRENGTH/HARDNESS RELATIONSHIPS - TESTS USING GREEN WOOD

It is generally accepted that increasing the moisture content of wood gradually decreases the strength properties until the fibre saturation point is reached. The mechanism of strength loss due to increasing water content has been discussed in an earlier section.

(i) Density

Although it is apparent that all strength properties tested are lower for green wood than for dry wood (see Table pp. 246-7, Appendix G) it appears that the relationships between the different properties is somewhat different. As the graphs in Figs 33 to 38 show, there is significantly more scatter in the data points for green wood than is shown for air dry wood. Initially, the values of R^2 were seen to be extremely low, particularly for the Wedge Hardness/density relationship. This ranged from 0.3292 to 0.5735. One timber appeared to be showing an extremely low Wedge Hardness value compared with its general strength properties. The timber was southern rata and it was suspected that, as all the timbers had been taken from the dry to the wet state, the rata may still be relatively dry away from the surface. However, no moisture content gradient of significance was detected, but freshly felled green southern rata was substituted and the tests repeated. The results, which are the ones documented, show the same effect. It is possible that the fibres on the surface of the wood are somewhat more permeable than the internal fibres due to disturbance by machining. As the wedge test is very much confined to indentation of the fibres close to the surface, it is possible that wedge hardness being more highly affected by moisture than other strength properties - these relying on the whole fibre matrix. However, it is not unreasonable to assume that if this mechanism occurs in southern rata it may well occur in other species. If it does, the effect is not apparent, even in closely related timbers such as pohutukawa and northern rata. It may well be a function of the exceedingly high density (1274 kg/m^3) of the southern rata, in that swelling occurs more easily at the surface than in the internal fibres.

The computation of linear regressions using the same data, but removing the weighting of the southern rata, improves the values of R^2 considerably. The range of values of R^2 for Wedge Hardness versus adjusted density becomes 0.5342 to 0.6557 as compared with 0.3292 to 0.5735 with the inclusion of southern rata. (Tables 19 and 20).

(ii) Janka Hardness (Table 19)

The relationship between Wedge Hardness and Janka Hardness is even less well correlated than the Wedge Hardness/ density relationship. Even without the adverse effect of southern rata (Table 20) the strongest relationship is for the 120° angle which shows an R^2 value of 0.5718 for the linear case and $R^2 = 0.5728$ after addition of the quadratic term, virtually no improvement. This contrasts strongly with the relationship between Janka Hardness and density for green wood where the following equations apply:

$$H_J = 0.0841\rho - 10.995 \qquad R^2 = 0.7476$$

and

$$H_J = 0.1241 + 0.00003\rho^2 - 22.565 \qquad R^2 = 0.7614$$

where H_J is Janka Hardness in N/mm^2 and ρ is density in kg/m^3.

The graphs of Wedge Hardness versus Janka Hardness, Fig. 34 (a) to (g), indicate an enormous amount of scatter. The fact that the Janka/Wedge relationship is worse than the Wedge/density and the Janka density relationships would indicate that the wedge tools are responding to factors which the Janka tool is either not responding to or to which it is much less sensitive. The indication here is that increased penetration of the Janka tool over the wedges reduces the likelihood of wet surface fibres influencing the Janka Hardness values. A further indication of this is that the blunter indenters - notably the 170° wedge - show significantly worse R^2 values than the sharper angles.

The resistance to flow of water within the wood may add to the influence - particularly by causing local variations in hardness. It is evident from the results of Wedge Hardness tests given in Tables 27A and 27B that wet balsa is "harder" than dry balsa. This is almost certainly due to the resistance to flow of water within the wood.

(iii) Bending Strength

(a) Modulus of Rupture (Table 21).

Again correlations are much weaker than for wood in the air dry state. A large improvement is evident by addition of the quadratic term. It is notable that this is negative - tipping the curve down to include the southern rata value. On exclusion of the southern rata that R^2 values become considerably better (Table 22) and are improved, though less than in the previous case, by the quadratic term. It is conspicuous that the sharper angles show the strongest correlation.

(b) Modulus of Elasticity (Table 21).

The Modulus of Elasticity, which correlated very well with density in the dry state, shows a very weak relationship with Wedge Hardness. This is surprising, as the USDA handbook shows MOE to be less affected than other strength properties by moisture (see p.30). As with MOR, the relationship without southern rata is stronger, and again there is less improvement on addition of the quadratic case than before. The weaker correlations are with the blunt indenters, R^2 increasing as the angle decreases.

For both MOE and MOR, the correlations with density are excellent. The following equations are obtained.

$$\text{MOR} = 0.0129\rho - 1.469 \qquad R^2 = 0.8713$$

and

$$\text{MOR} = 0.633 + 0.0057\rho + 0.00001\rho^2 \qquad R^2 = 0.9453$$

$$\text{MOE} = 0.018\rho - 2.503 \qquad R^2 = 0.8007$$

and

$$\text{MOE} = 1.538 + 0.004\rho + 0.00001\rho^2 \qquad R^2 = 0.8414$$

where MOR is in N/mm^2, MOE in N/mm and density, ρ, in kg/m^3.

(iv) Cleavage Strength parallel to the grain.

Green Wood.

The Wedge Hardness/cleavage strength correlations for green wood are considerably better than the bending strength correlations given above. However, the influence of southern rata here is much less marked, presumably because the cleavage strength of southern rata in the green state is not outstandingly high. It is noteworthy that the only improvements shown by removing the effect of low southern rata hardness values are in the linear cases. The negative quadratic term is, in this case, adequately predicting the value of Wedge Hardness of southern rata within the confidence limits imposed.

The ability of Wedge Hardness to predict cleavage strength of green wood is poorer than the predictive power of density. The cleavage strength density relationships are as follows:

$$\sigma_{c1} = 0.284\rho - 24.209 \qquad R^2 = 0.7933$$

$$\sigma_{c1} = 0.408\rho - 0.00009\rho^2 - 60.018 \qquad R^2 = 0.8056$$

where σ_{c1} is cleavage strength in N/mm, ρ is adjusted density in kg/m^3.

(v) Shear strength parallel to the grain. Green Wood

In this case the southern rata shows a low shear strength considering its density and its removal from the analysis does not improve the correlations at all. This is the one case where Wedge Hardness correlates better in the linear case than does density;

$$\tau = 0.0103\rho + 1.271 \qquad R^2 = 0.5808$$

is the equation for the shear strength (τ) versus density. However, the addition of a quadratic term to the equation improves the R^2 value enormously.

$$\tau = 0.0318\rho - 0.00002\rho^2 - 4.959 \qquad R^2 = 0.7896$$

In both cases τ is the shear strength in N/mm^2 ρ is adjusted density in kg/m^3.

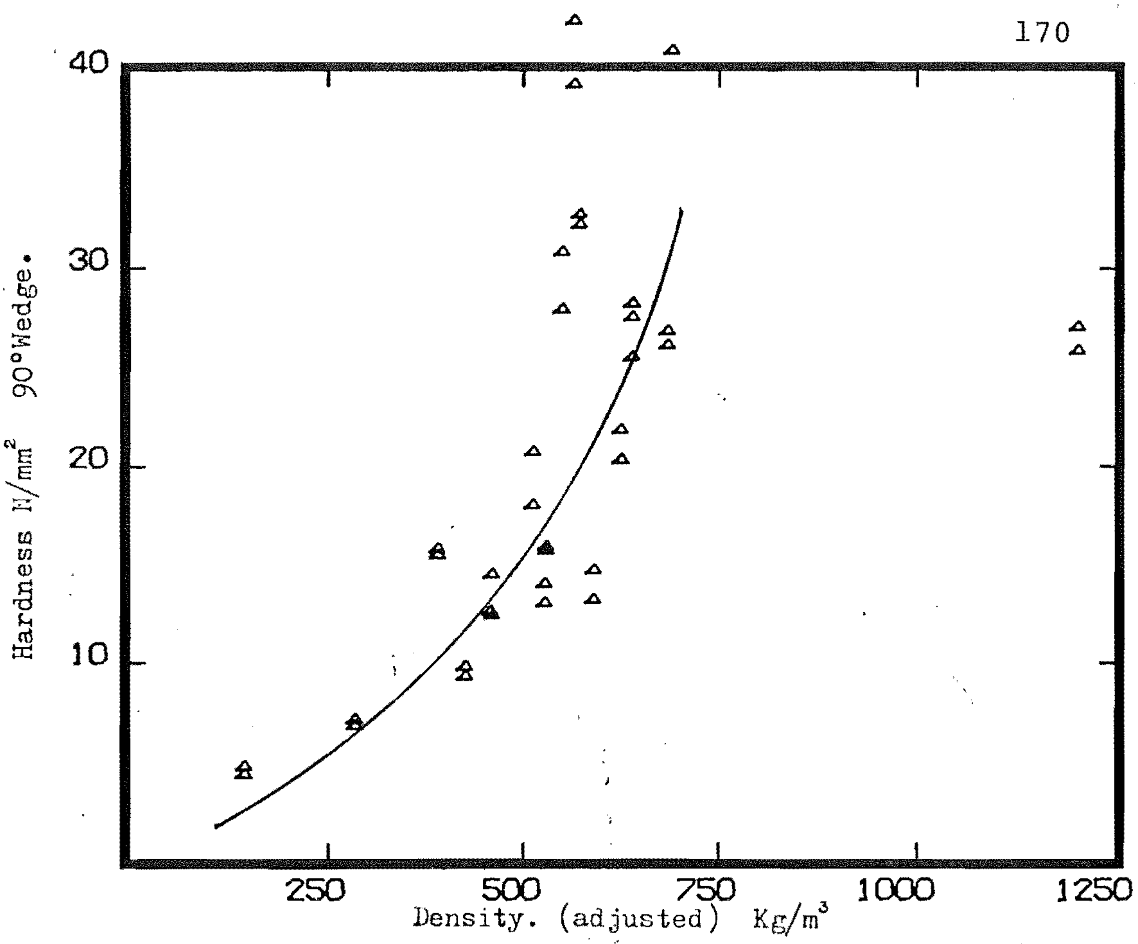
Wedge angle (degrees)	Constant	Coefficient of x	Coefficient of x^2	R^2
Wedge Hardness, H_w, v. Adjusted density (ρ). Green.				
90	4.489	0.029	-	0.3303
105	3.037	0.024	-	0.3501
120	2.751	0.018	-	0.3292
136	1.724	0.015	-	0.3896
150	1.313	0.011	-	0.3777
160	0.923	0.009	-	0.4429
170	0.675	0.006	-	0.4228
90	-14.563	0.095	-0.00005	0.4958
105	-11.196	0.073	-0.00004	0.4947
120	-8.373	0.057	-0.00003	0.4774
136	-6.344	0.043	-0.00002	0.5273
150	-4.852	0.032	-0.00002	0.5156
160	-3.659	0.025	-0.00001	0.5735
170	-2.683	0.018	-0.00001	0.5706
Wedge Hardness, H_W, v. Janka Hardness, H_J. Green.				
90	8.015	0.364	-	0.4696
105	6.006	0.298	-	0.4911
120	4.662	0.232	-	0.5006
136	3.783	0.175	-	0.5057
150	3.199	0.122	-	0.4189
160	2.651	0.096	-	0.4439
170	1.947	0.061	-	0.3830
90	2.175	0.774	-0.0053	0.5174
105	2.438	0.548	-0.0032	0.5190
120	1.840	0.430	-0.0026	0.5299
136	1.797	0.315	-0.0018	0.5312
150	1.675	0.229	-0.0014	0.4448
160	1.206	0.197	-0.0013	0.4839
170	0.823	0.140	-0.0010	0.4339

Table 19

Wedge angle (degrees)	Constant	Coefficient of x	Coefficient of x^2	R^2
Wedge Hardness, H_w, v. Adjusted density (ρ). Green.				
90	-8.869	0.057	-	0.5470
105	-7.320	0.046	-	0.5512
120	-5.294	0.035	-	0.5342
136	-4.239	0.027	-	0.5837
150	-3.289	0.021	-	0.5778
160	-2.400	0.016	-	0.6135
170	-1.696	0.011	-	0.6106
90	3.083	-0.0067	0.00007	0.5762
105	4.857	-0.0193	0.00008	0.5989
120	3.791	-0.0137	0.00006	0.5784
136	3.459	-0.0139	0.00005	0.6406
150	2.986	-0.0129	0.00004	0.6424
160	1.431	-0.0043	0.00002	0.6557
170	0.554	-0.0009	0.00001	0.6400
Wedge Hardness, H_w, v. Janka Hardness, H_J. Green.				
90	5.752	0.454	-	0.5380
105	4.306	0.365	-	0.5483
120	3.236	0.289	-	0.5718
136	2.893	0.211	-	0.5460
150	2.598	0.146	-	0.4465
160	2.309	0.109	-	0.4408
170	1.717	0.070	-	0.3816
90	4.599	0.544	-0.00132	0.5396
105	4.678	0.336	0.00043	0.5486
120	3.804	0.244	0.00065	0.5728
136	2.909	0.209	0.00002	0.5460
150	2.333	0.166	0.00030	0.4472
160	1.128	0.190	-0.00118	0.4586
170	0.798	0.142	-0.00106	0.4114

Table 20

Data excluding southern rata



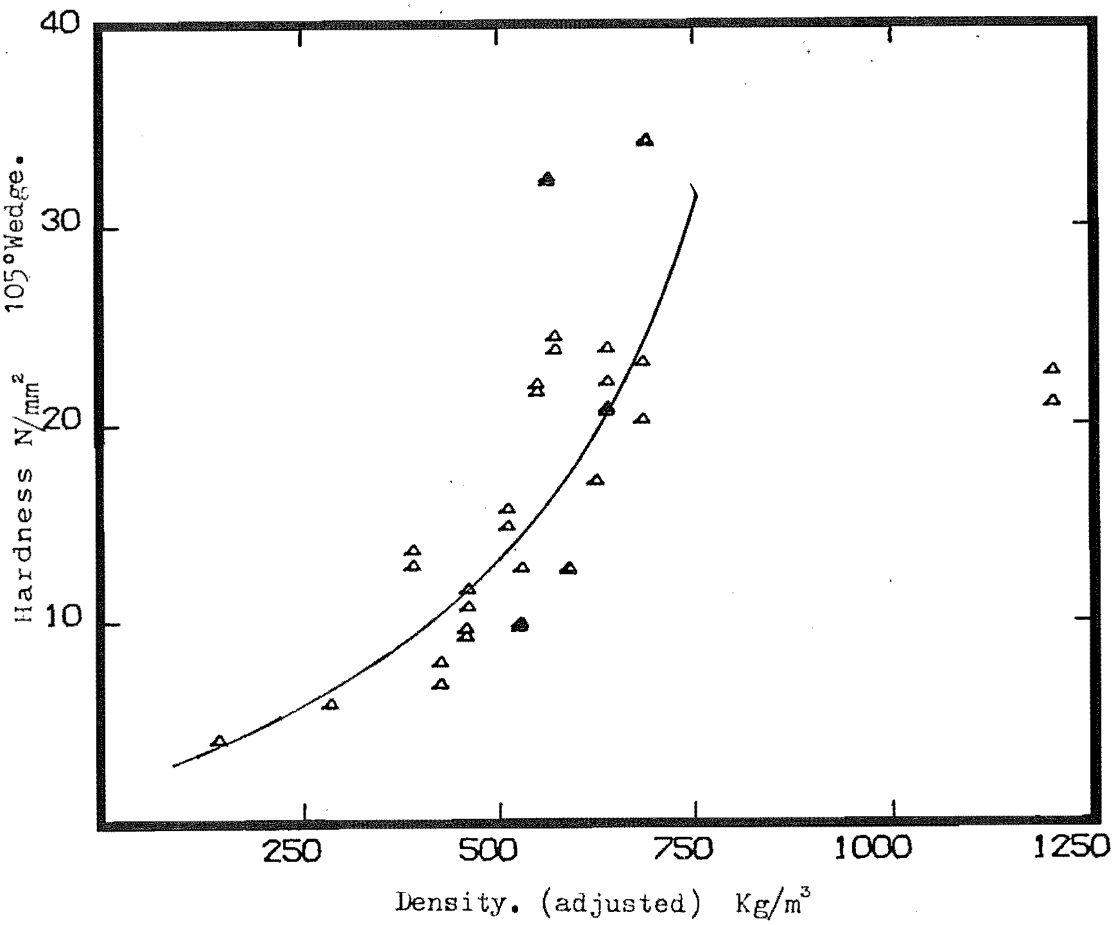
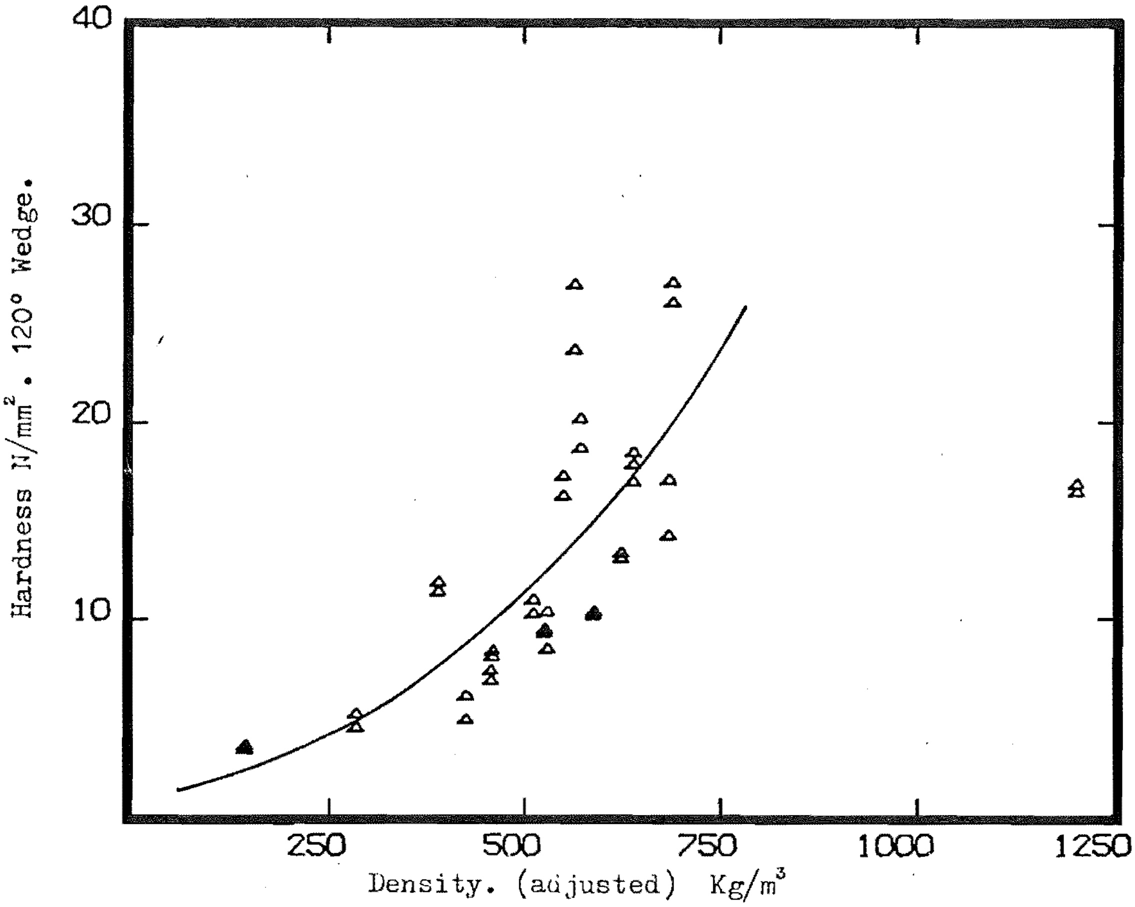


Fig. 33 - (a) and (b) Wedge Hardness versus Adjusted Density. Green Wood.



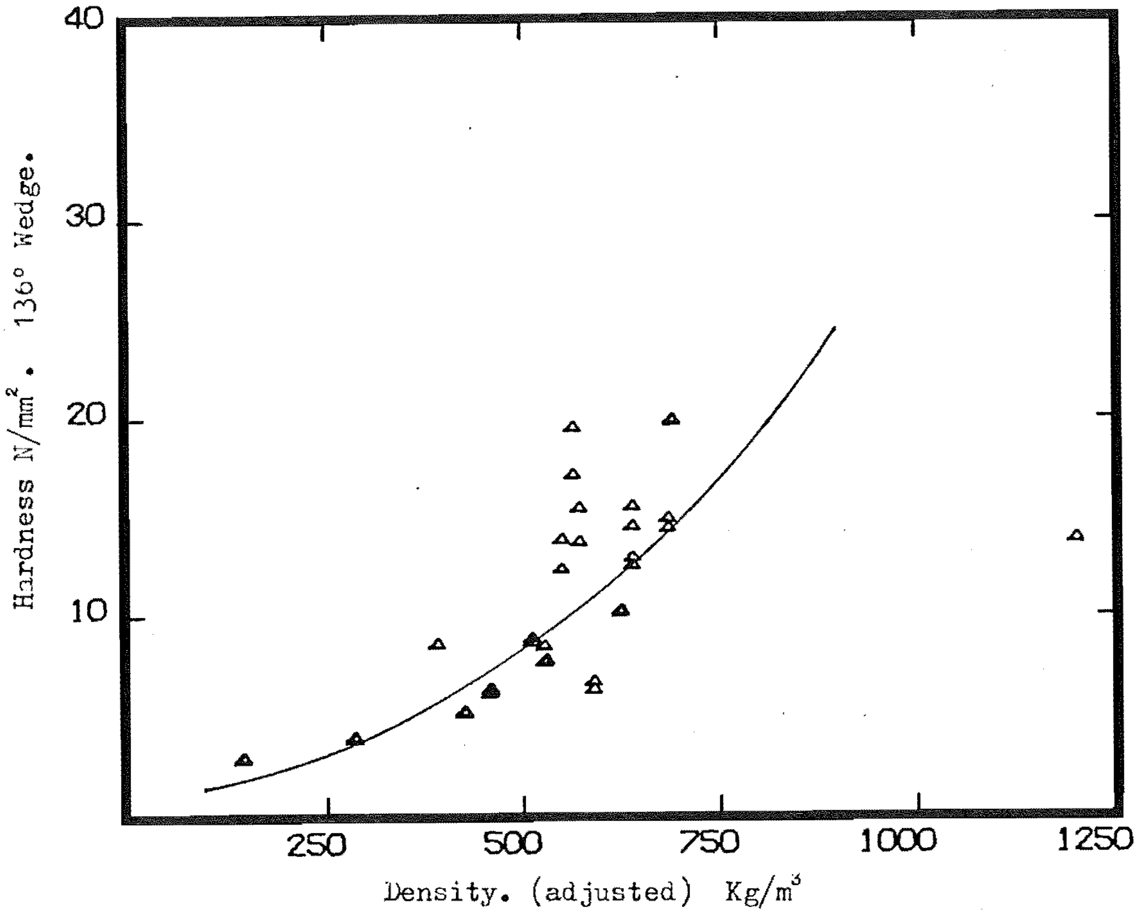
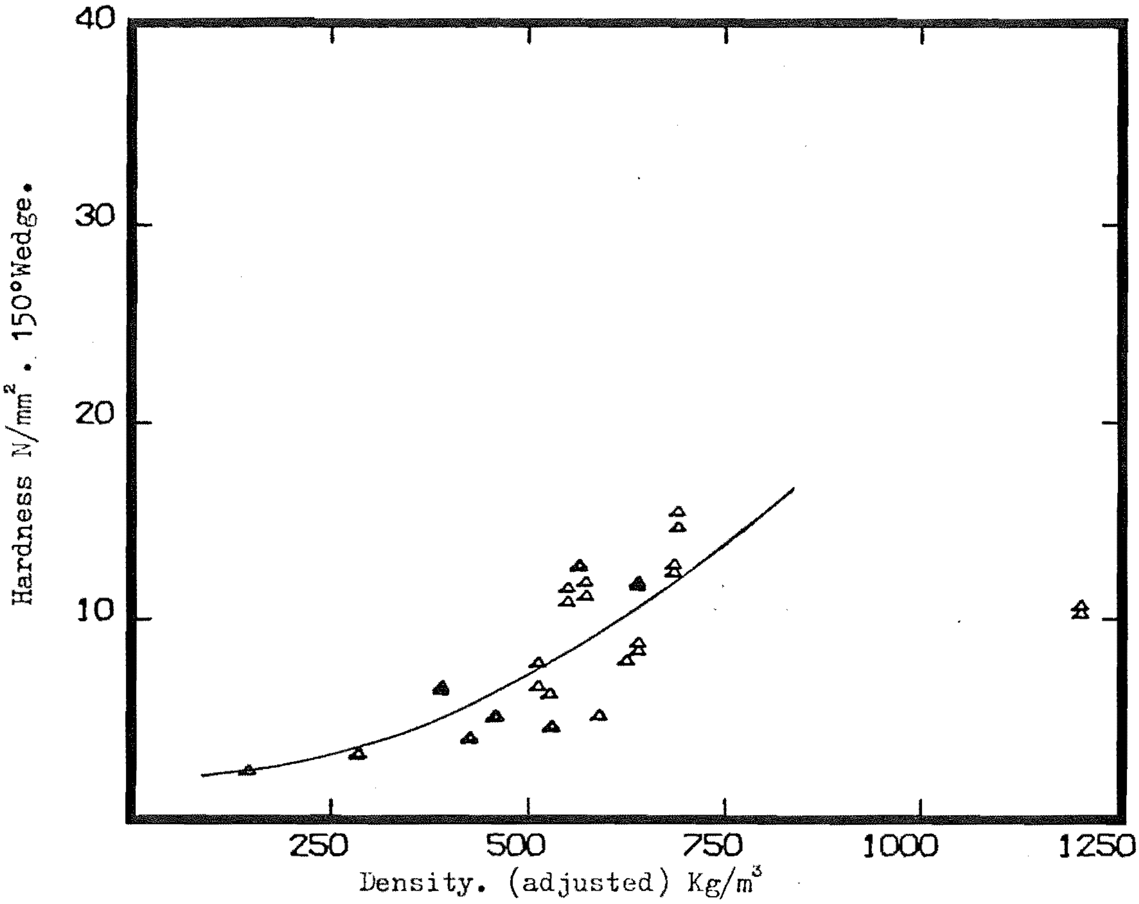


Fig. 33 - (c) and (d) Wedge Hardness versus Adjusted Density. Green Wood.



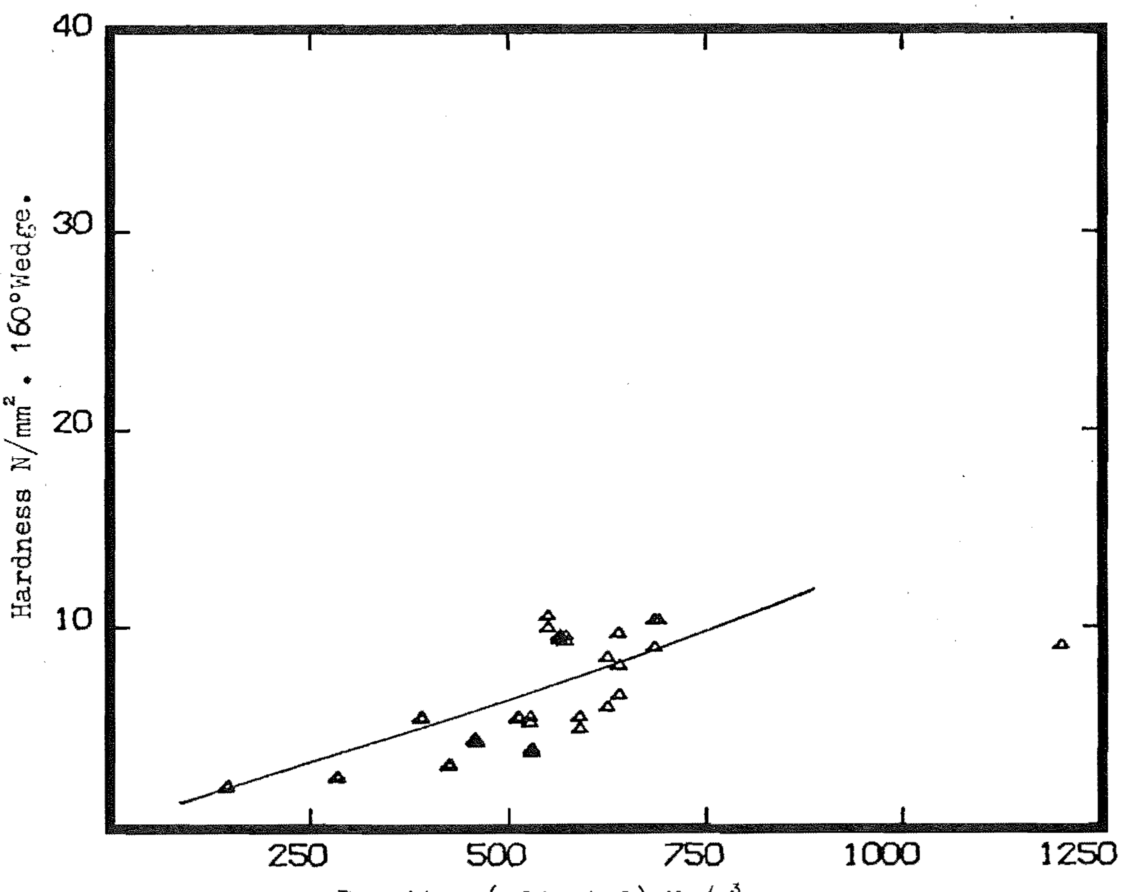


Fig. 33 - (e) and (f) Wedge Hardness versus Adjusted Density. Green Wood.

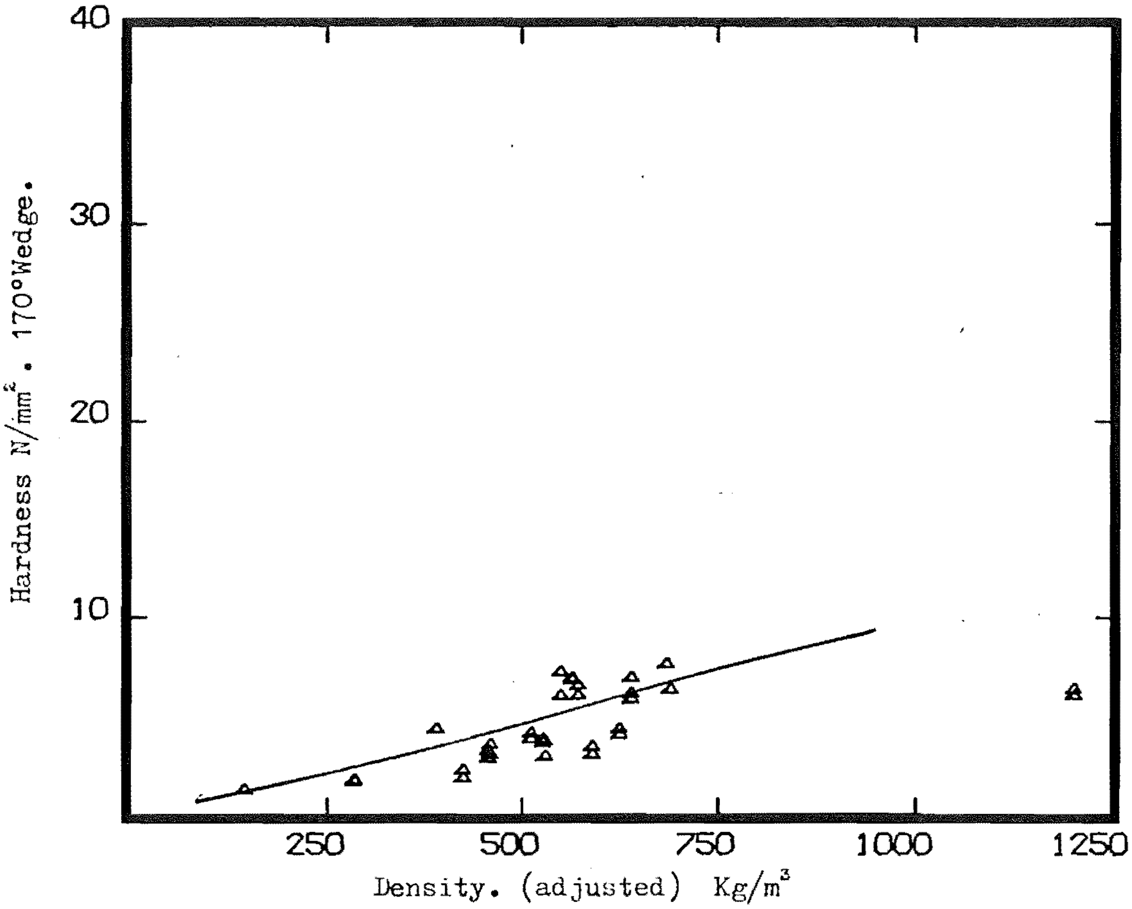
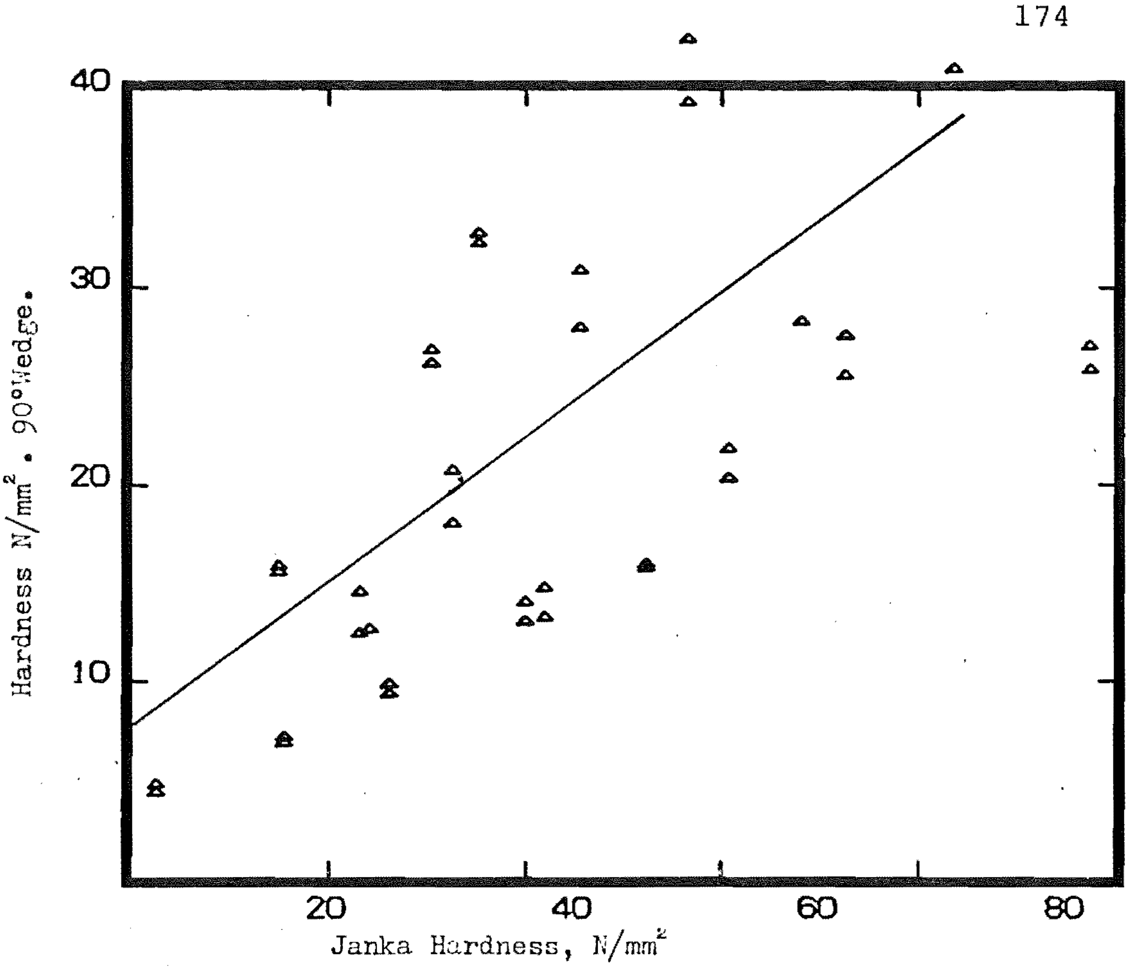


Fig. 33 - (g) Wedge Hardness versus Adjusted Density.
Green Wood.



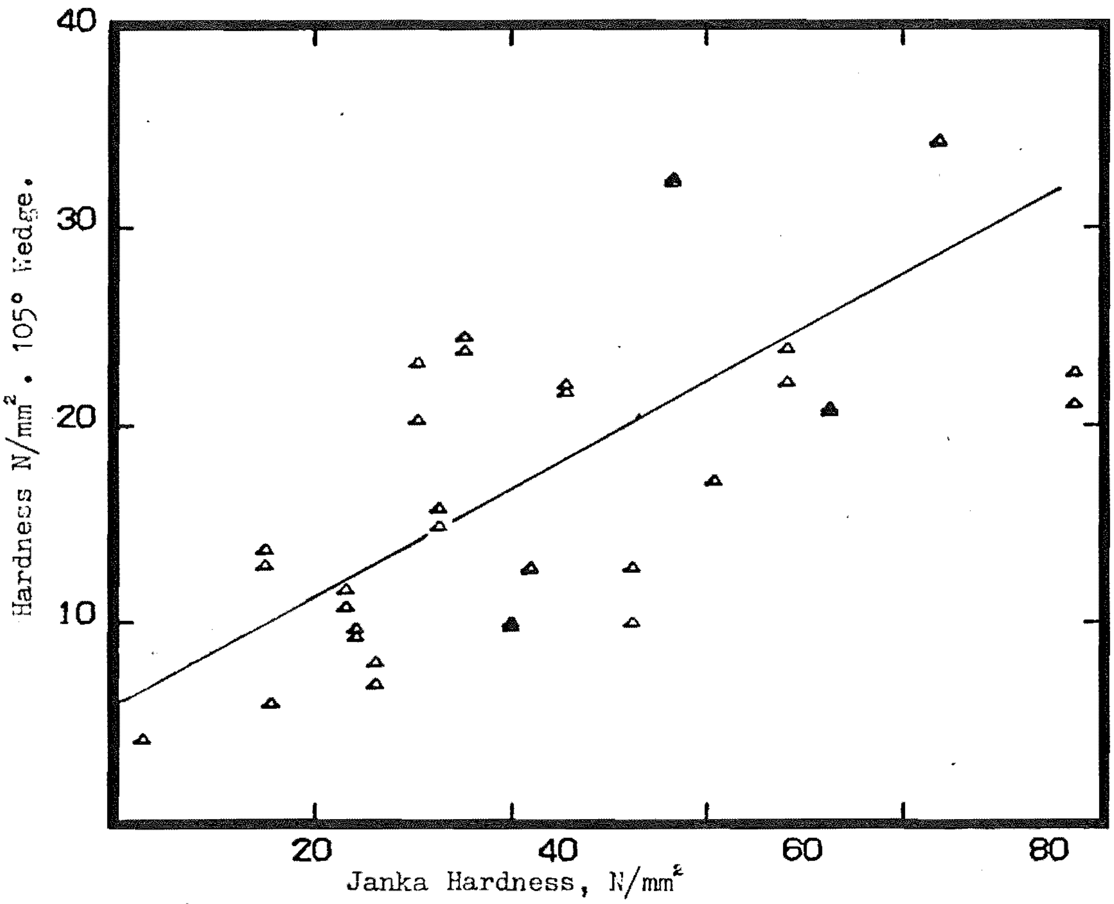
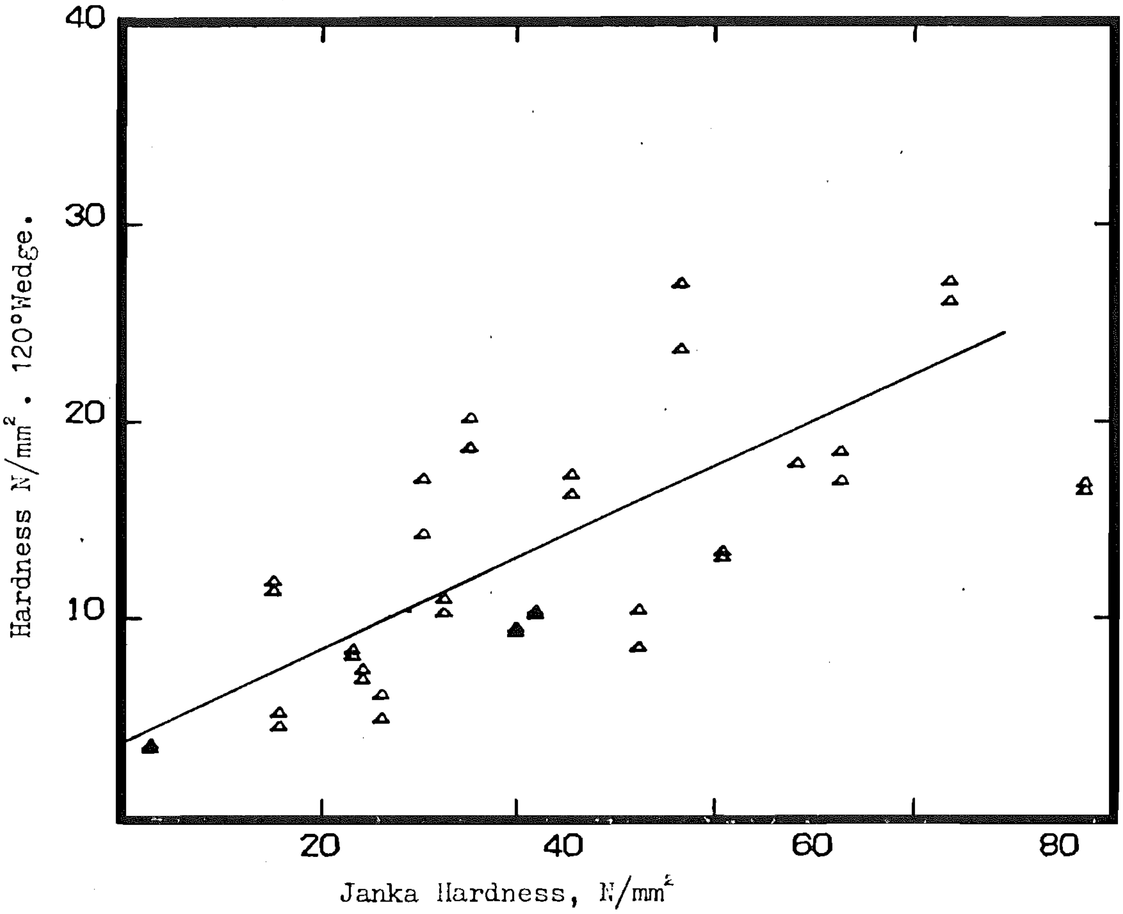


Fig. 34 - (a) and (b) Wedge Hardness versus Janka Hardness for Green Wood.



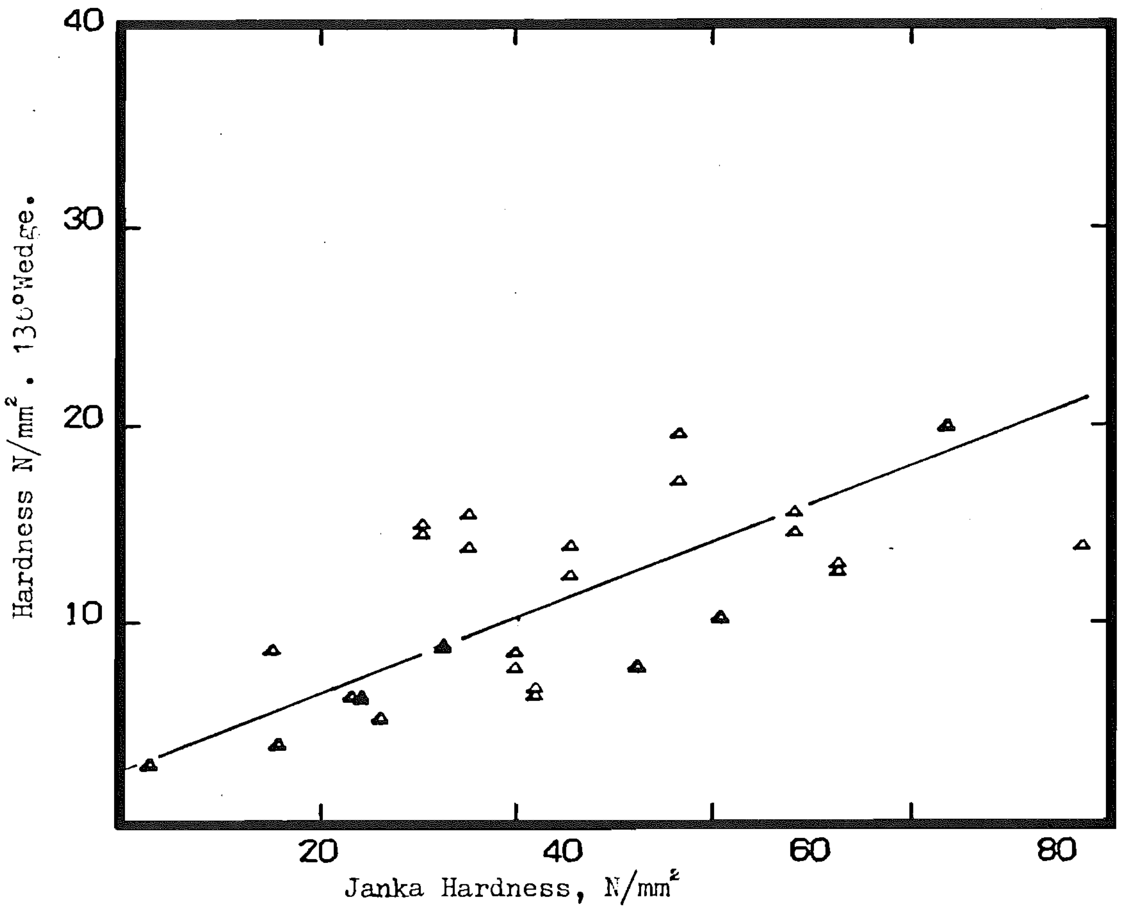
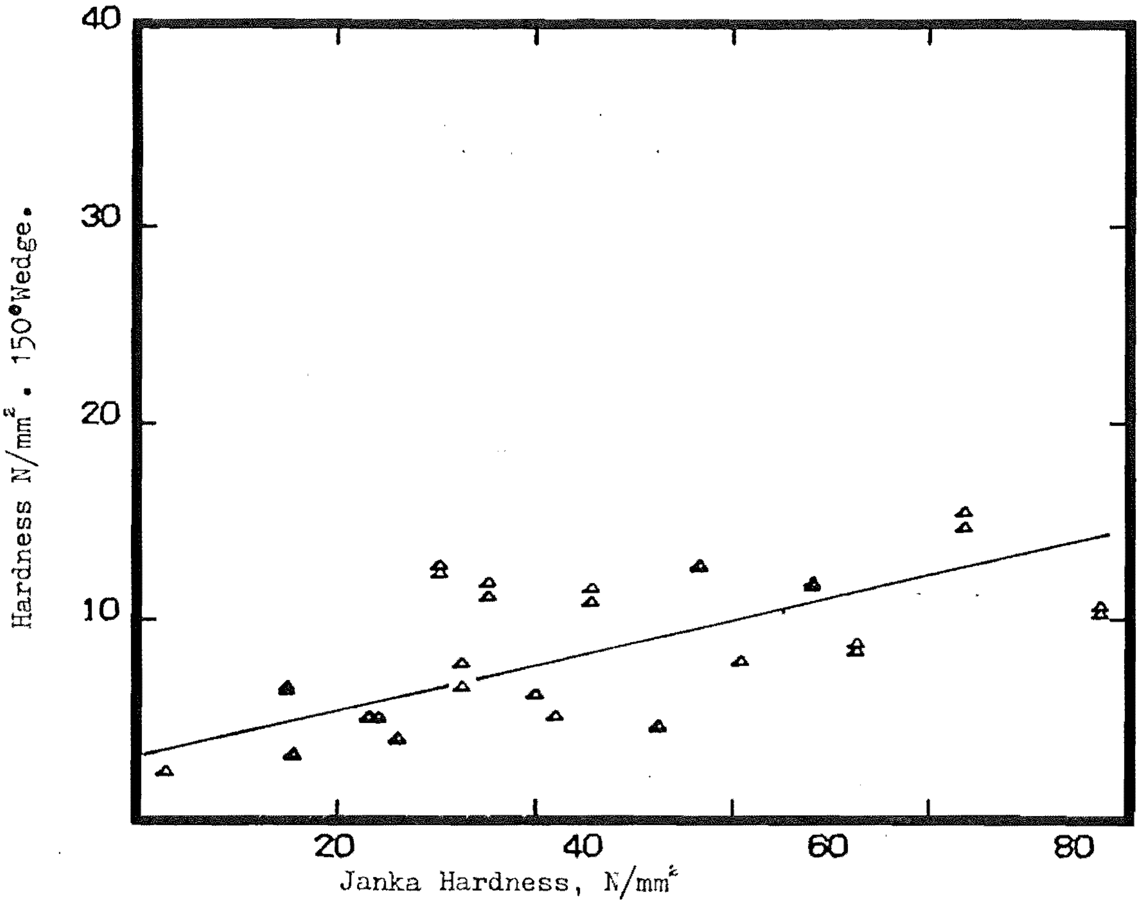


Fig. 34 - (c) and (d) Wedge Hardness versus Janka Hardness for Green Wood.



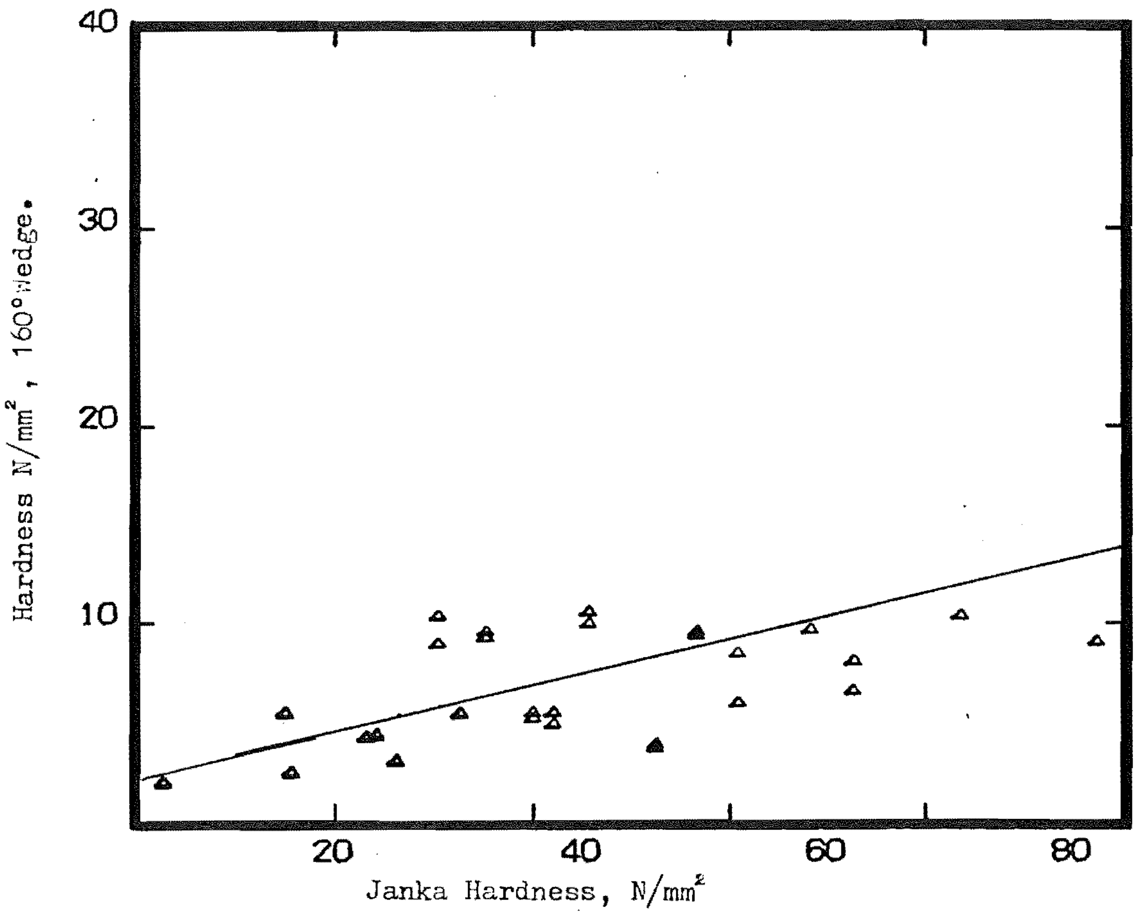


Fig. 34 - (e) and (f) Wedge Hardness versus Janka Hardness for Green Wood.

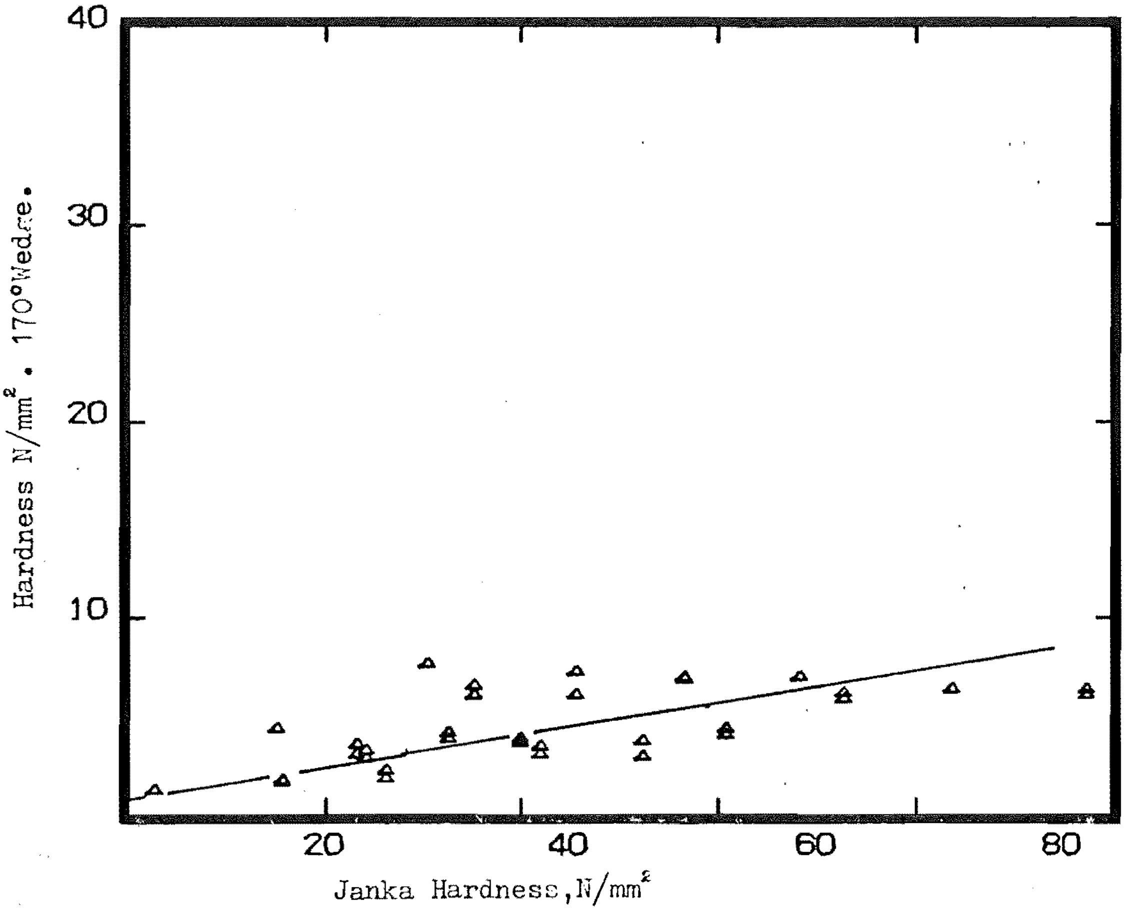


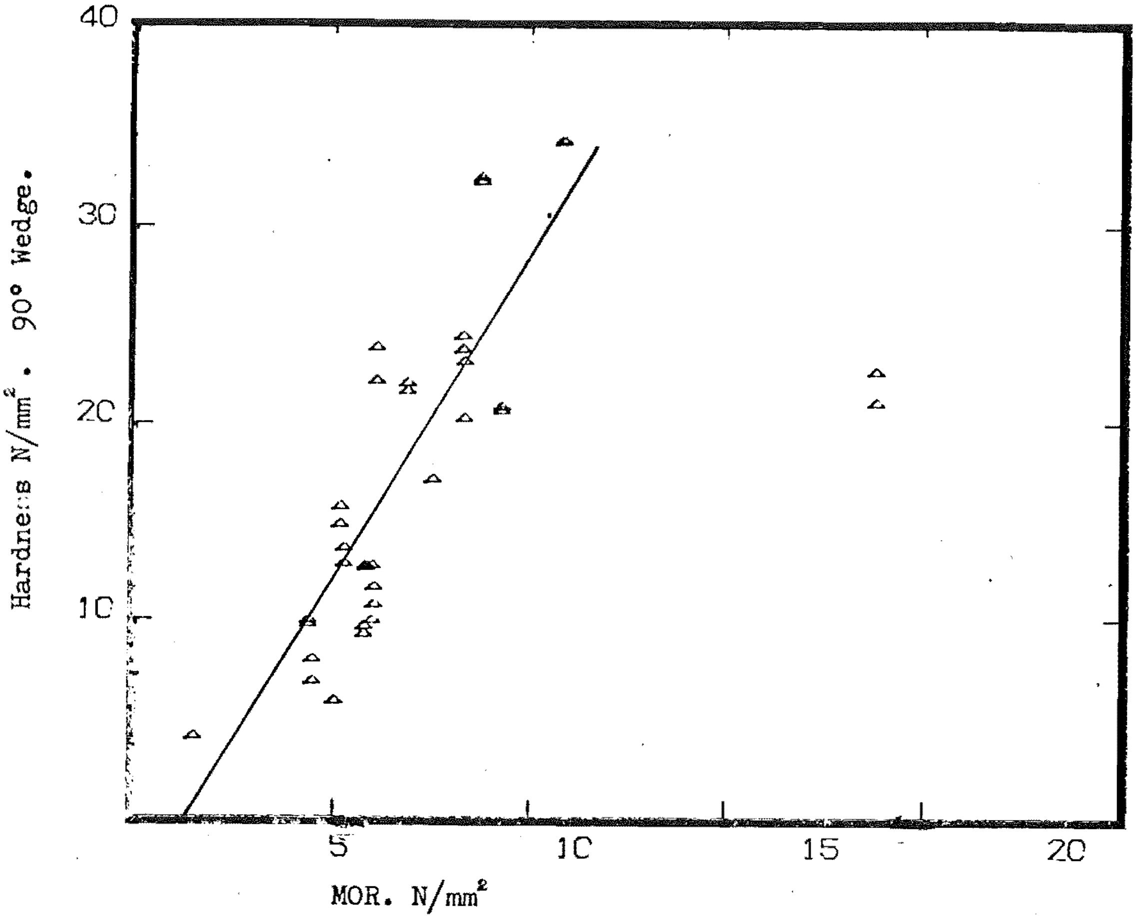
Fig. 34 - (g) Wedge Hardness versus Janka Hardness for Green Wood.

Wedge angle (degrees)	Constant	Coefficient of x	Coefficient of x^2	R^2
Wedge Hardness, H_w, v. Modulus of Rupture in Bending. Green.				
90	7.810	2.293	-	0.3706
105	5.746	1.891	-	0.3947
120	4.715	1.428	-	0.3773
136	3.636	1.114	-	0.4055
150	2.869	0.815	-	0.3727
160	2.084	0.642	-	0.3970
170	1.686	0.427	-	0.3702
90	-3.740	9.128	0.424	0.6695
105	-10.839	7.151	-0.326	0.6718
120	-8.143	5.506	-0.253	0.6567
136	-5.478	4.004	-0.179	0.6533
150	-3.973	2.985	-0.135	0.6125
160	-2.531	2.201	-0.097	0.6092
170	-1.883	1.559	-0.070	0.6060
Wedge Hardness, H_w, v. Modulus of Elasticity, E_b. Green.				
90	10.463	1.425	-	0.2933
105	8.043	1.159	-	0.3040
120	6.457	0.874	-	0.2899
136	5.076	0.670	-	0.3011
150	4.055	0.472	-	0.2558
160	3.276	0.377	-	0.2813
170	2.225	0.259	-	0.2790
90	-8.000	5.933	-0.203	0.5863
105	-6.075	4.607	-0.155	0.5722
120	-4.451	3.537	-0.119	0.5585
136	-2.414	2.499	-0.082	0.5246
150	-1.319	1.784	-0.059	0.4535
160	-0.448	1.287	-0.041	0.4441
170	-0.593	0.947	-0.031	0.4753

Table 21

Wedge angle (degrees)	Constant	Coefficient of x	Coefficient of x^2	R^2
Wedge Hardness, H_w, v. Bending strength, MOR. Green.				
90	-6.661	5.378	-	0.7383
105	-5.616	4.313	-	0.7482
120	-4.160	3.319	-	0.7398
136	-2.590	2.441	-	0.7157
150	-1.734	1.796	-	0.6631
160	-0.710	1.302	-	0.6102
170	-0.477	0.888	-	0.5935
90	-0.730	2.670	0.273	0.7502
105	0.548	1.498	0.284	0.7685
120	1.091	0.921	0.242	0.7644
136	0.666	0.954	0.150	0.7326
150	0.208	0.909	0.089	0.6734
160	-0.834	1.359	-0.006	0.6103
170	-1.161	1.200	-0.032	0.5982
Wedge Hardness, H_w, v. Bending Strength, MOE. Green.				
90	-3.212	3.752	-	0.6348
105	-2.419	2.939	-	0.6140
120	-1.739	2.269	-	0.6106
136	-0.429	1.607	-	0.5481
150	0.227	1.123	-	0.4579
160	0.743	0.809	-	0.4162
170	0.324	0.583	-	0.4508
90	3.398	1.181	0.215	0.6531
105	2.681	0.956	0.160	0.6312
120	3.201	0.347	0.160	0.6375
136	1.875	0.711	0.075	0.5585
150	0.805	0.898	0.188	0.4591
160	0.093	1.061	-0.021	0.4187
170	-0.307	0.828	-0.020	0.4557

Table 22 - Data excluding southern rata



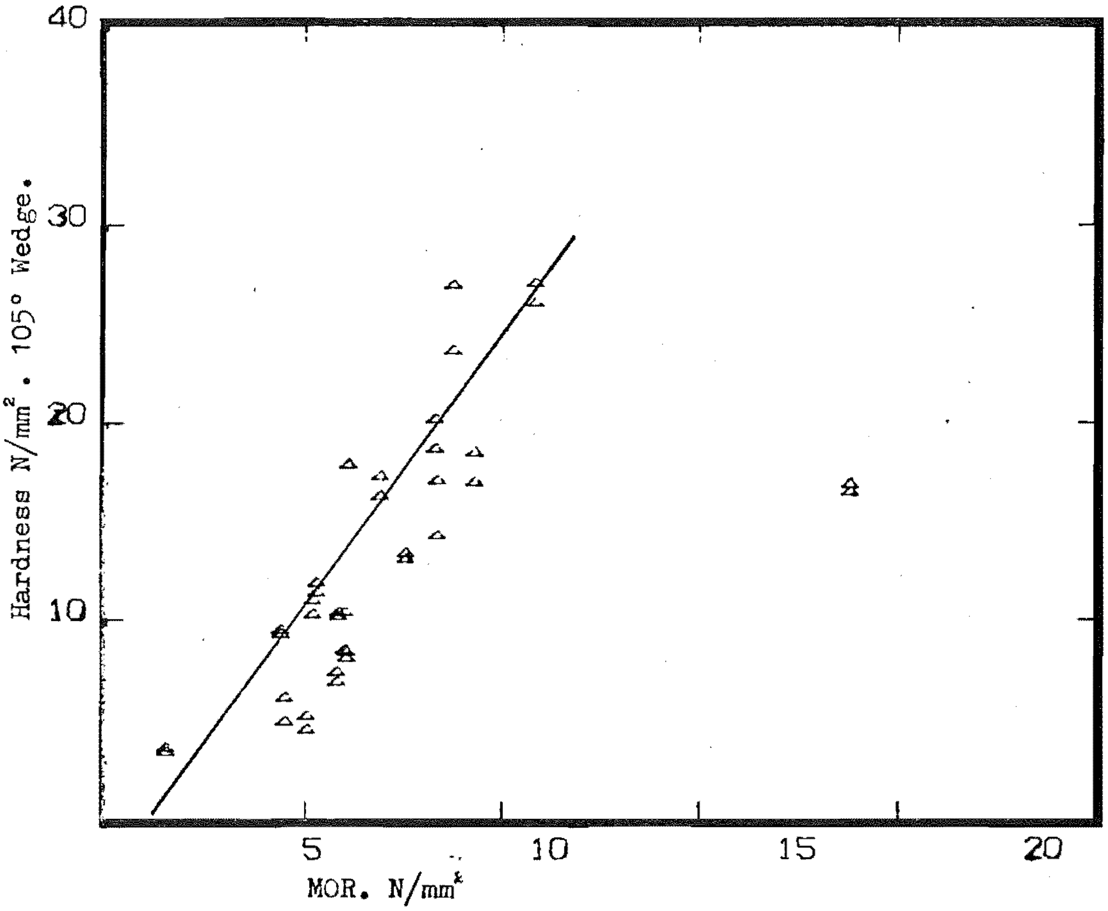
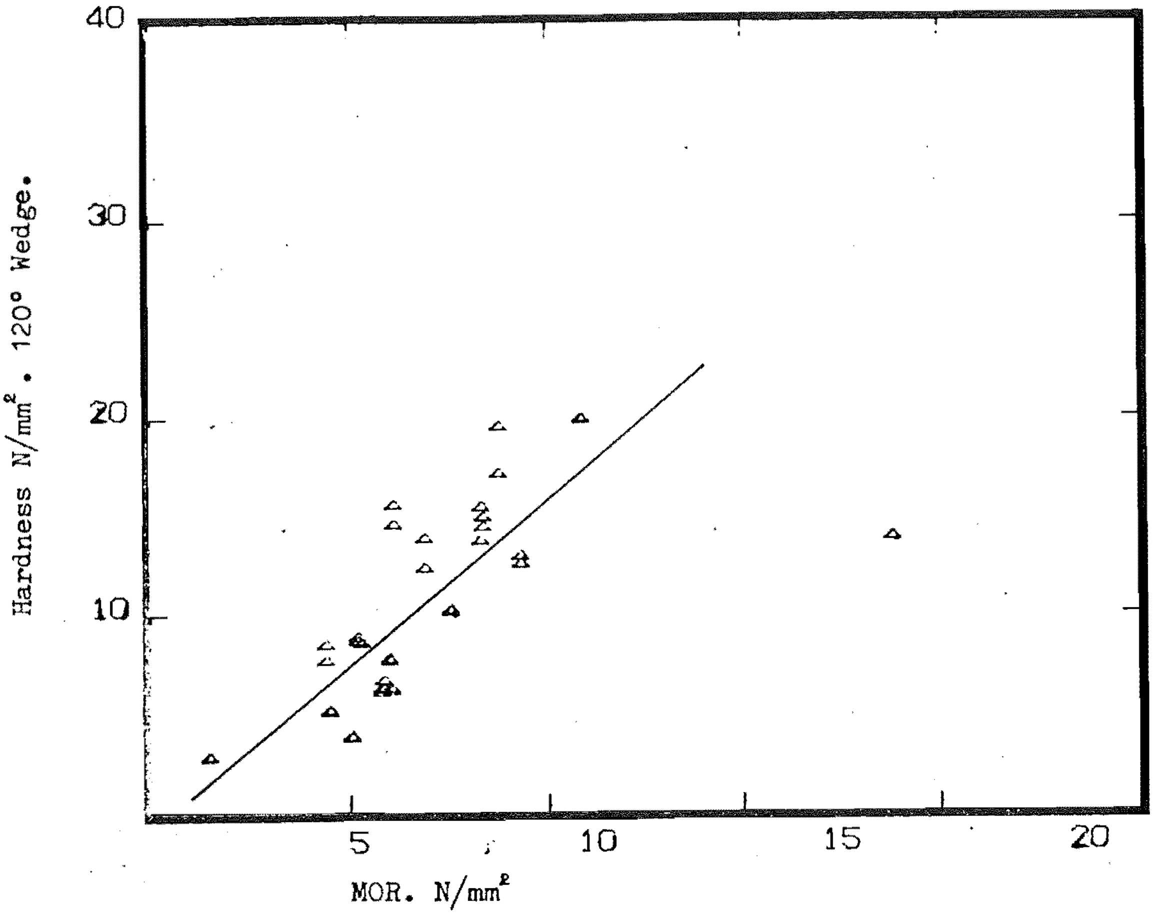


Fig. 35 - (a) and (b) Wedge Hardness versus Modulus of Rupture in Bending. Green Wood.



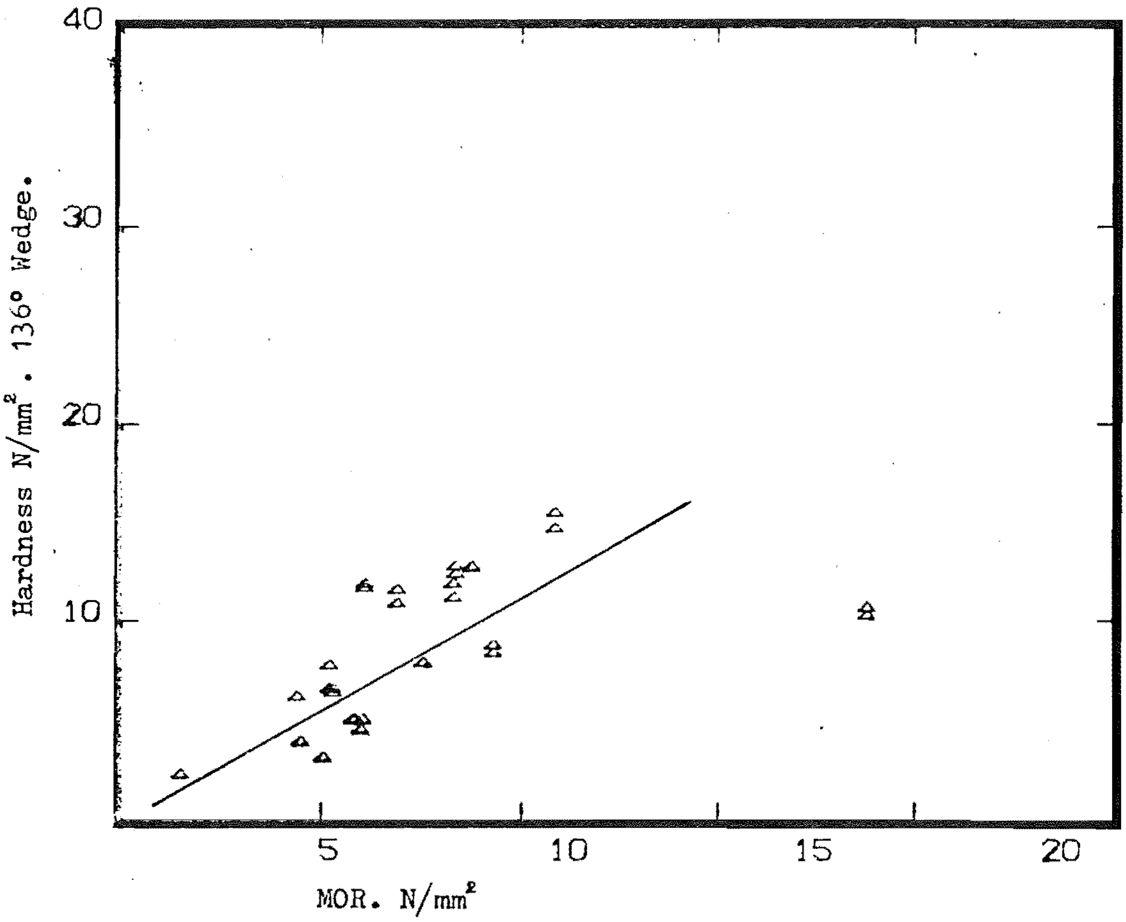
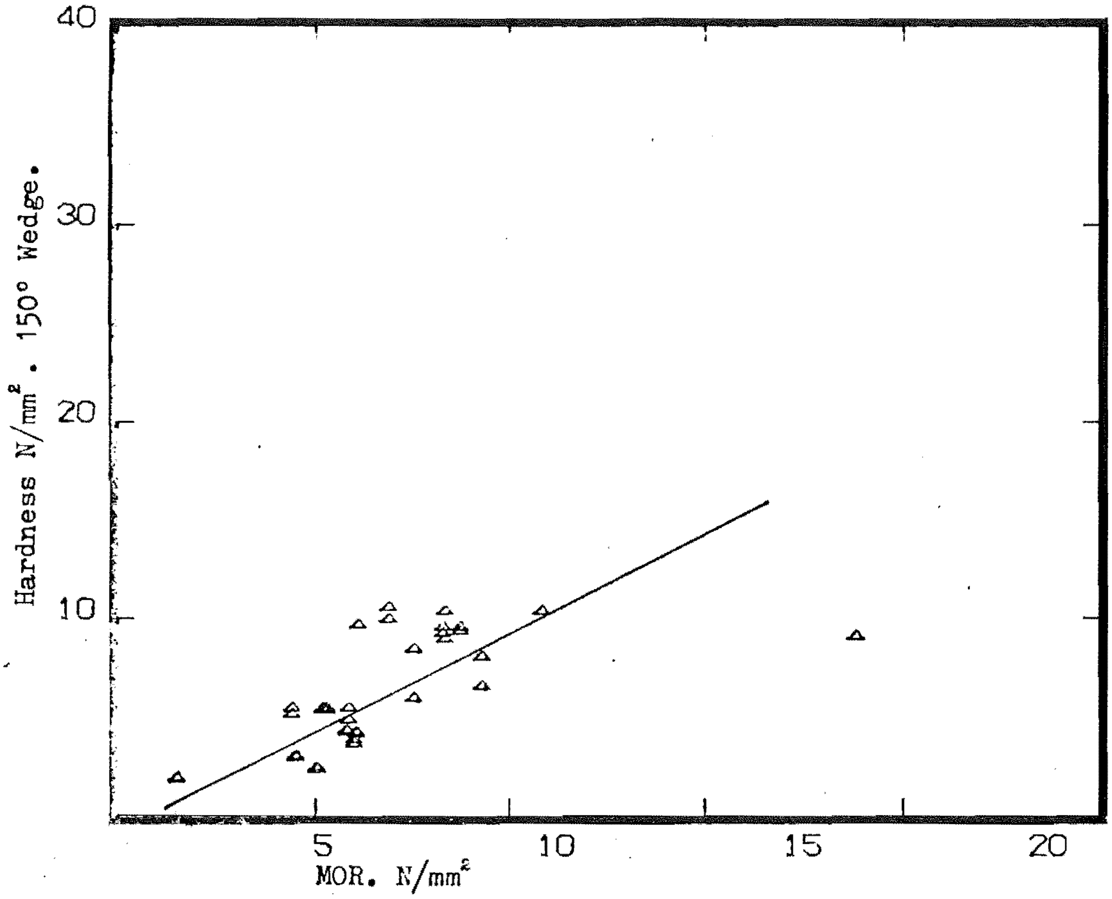


Fig. 35 - (c) and (d) Wedge Hardness versus Modulus of Rupture in Bending. Green Wood.



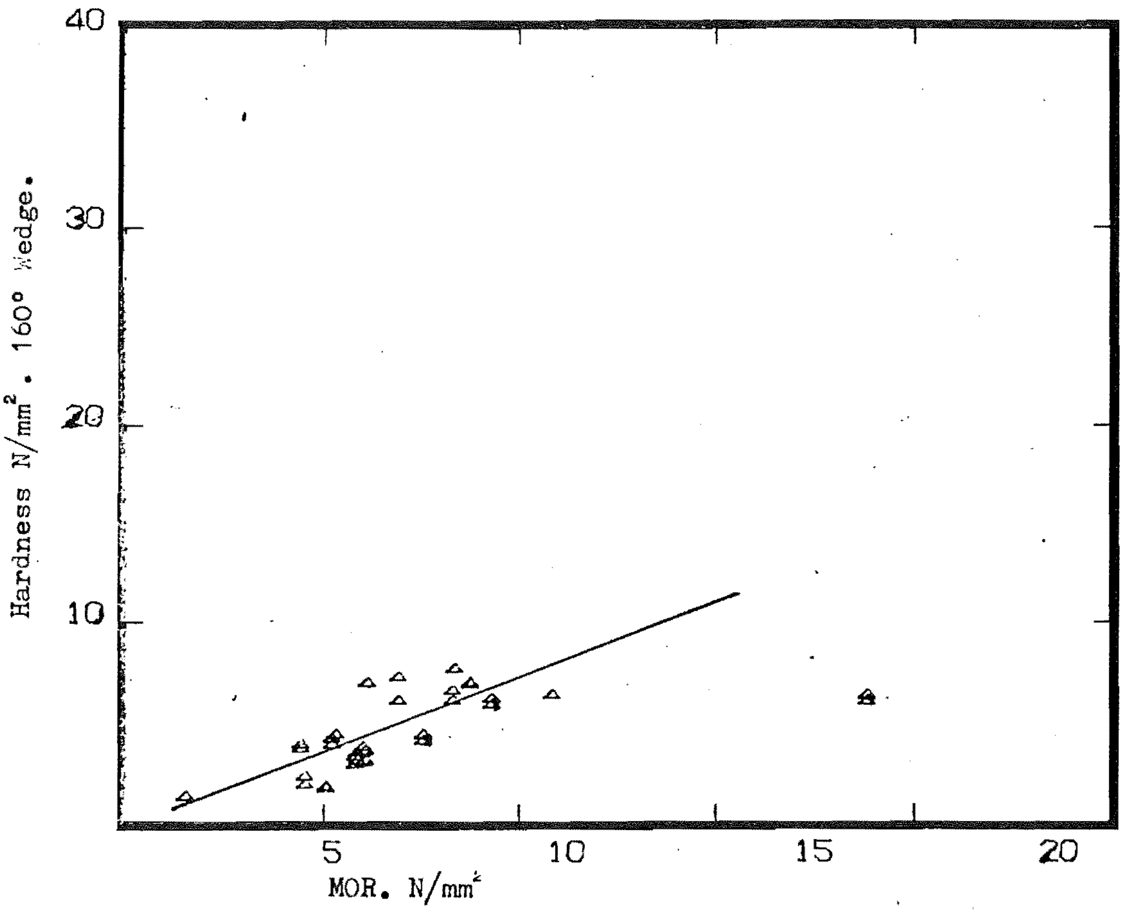
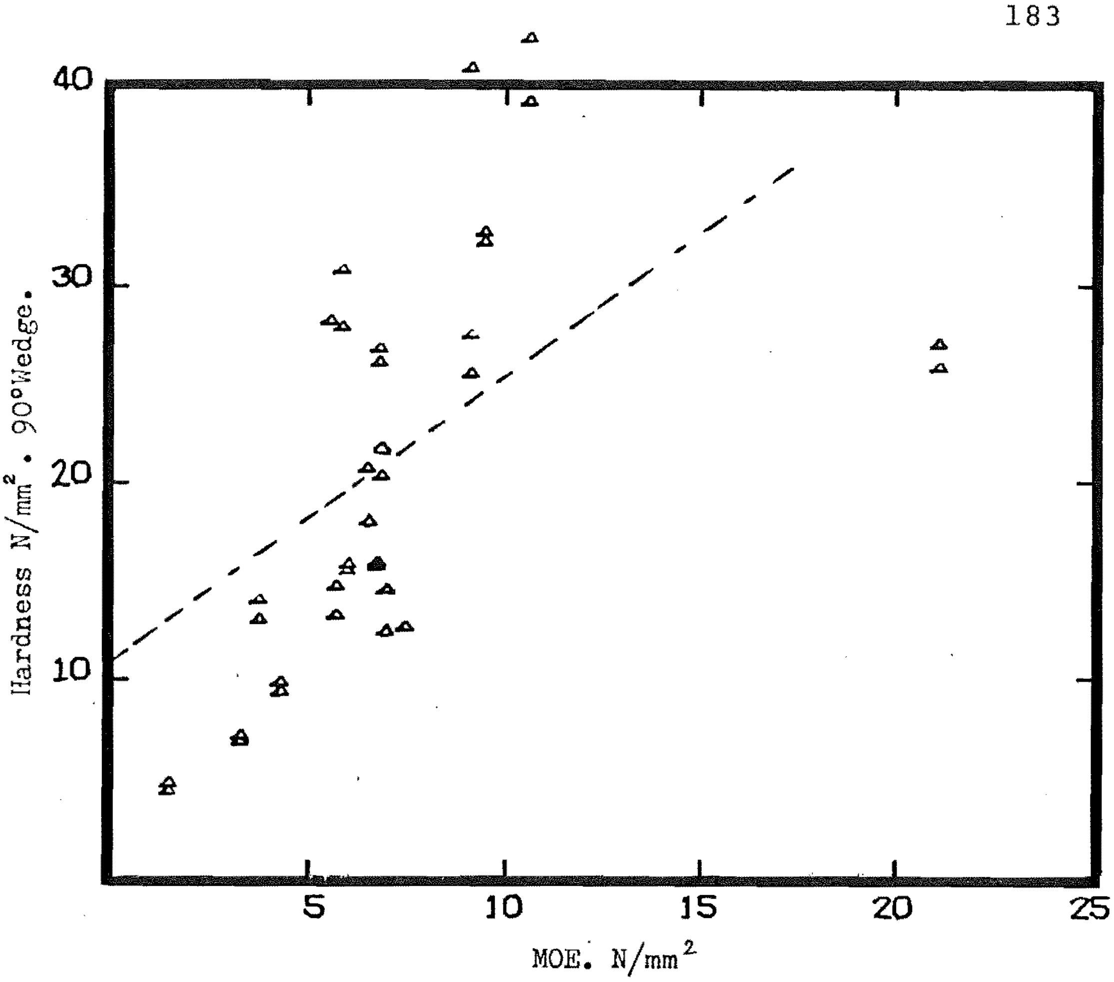


Fig. 35 - (e) and (f) Wedge Hardness versus Modulus of Rupture in Bending. Green Wood.



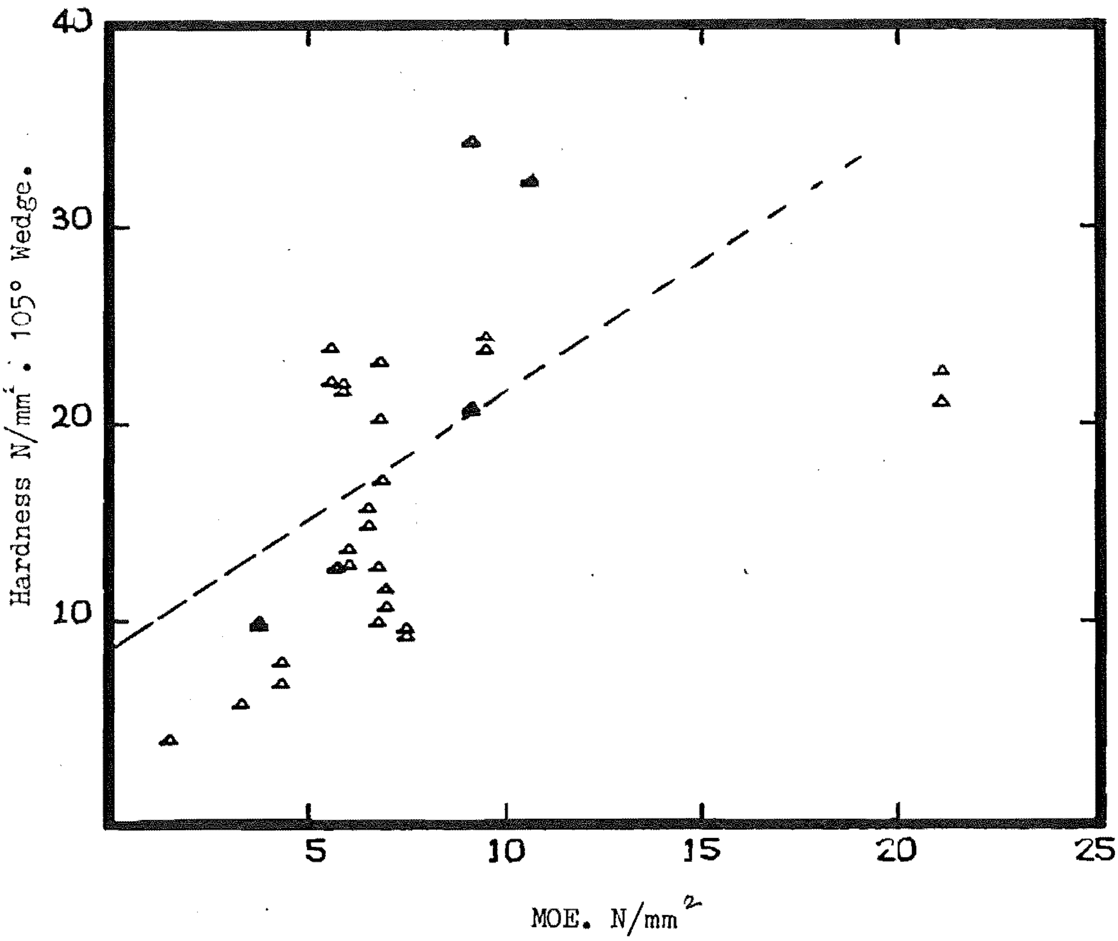
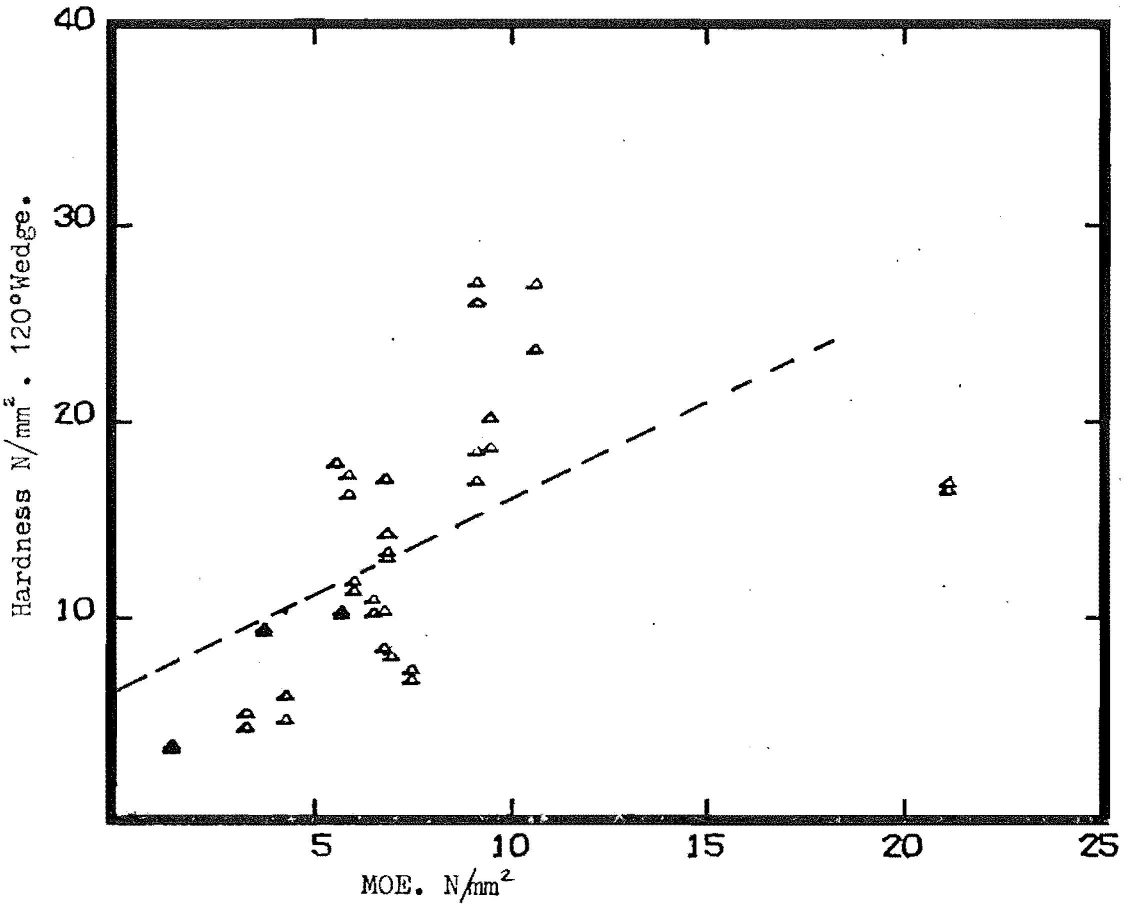


Fig. 36 - (a) and (b) Wedge Hardness versus Modulus of Elasticity in bending for Green Wood.



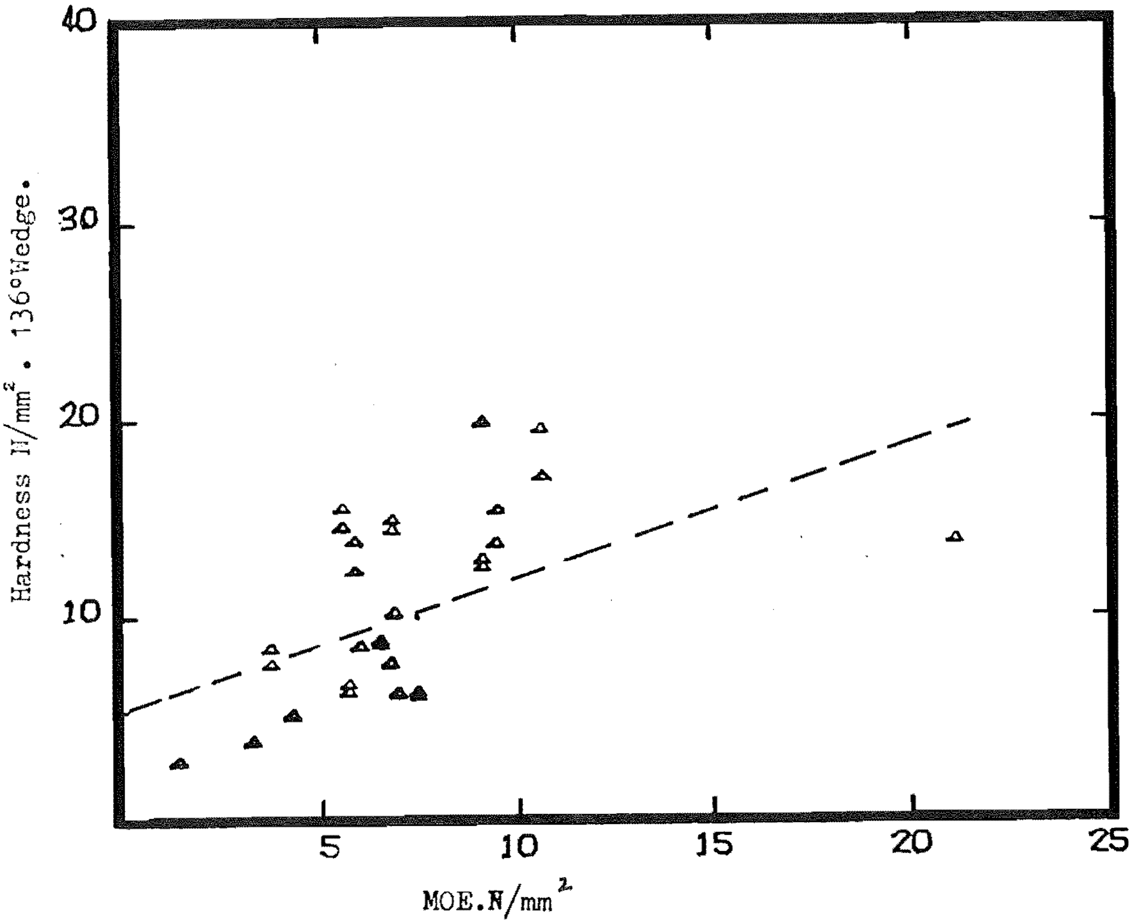


Fig. 36 - (c) and (d) Wedge Hardness versus Modulus of Elasticity in bending for Green Wood.

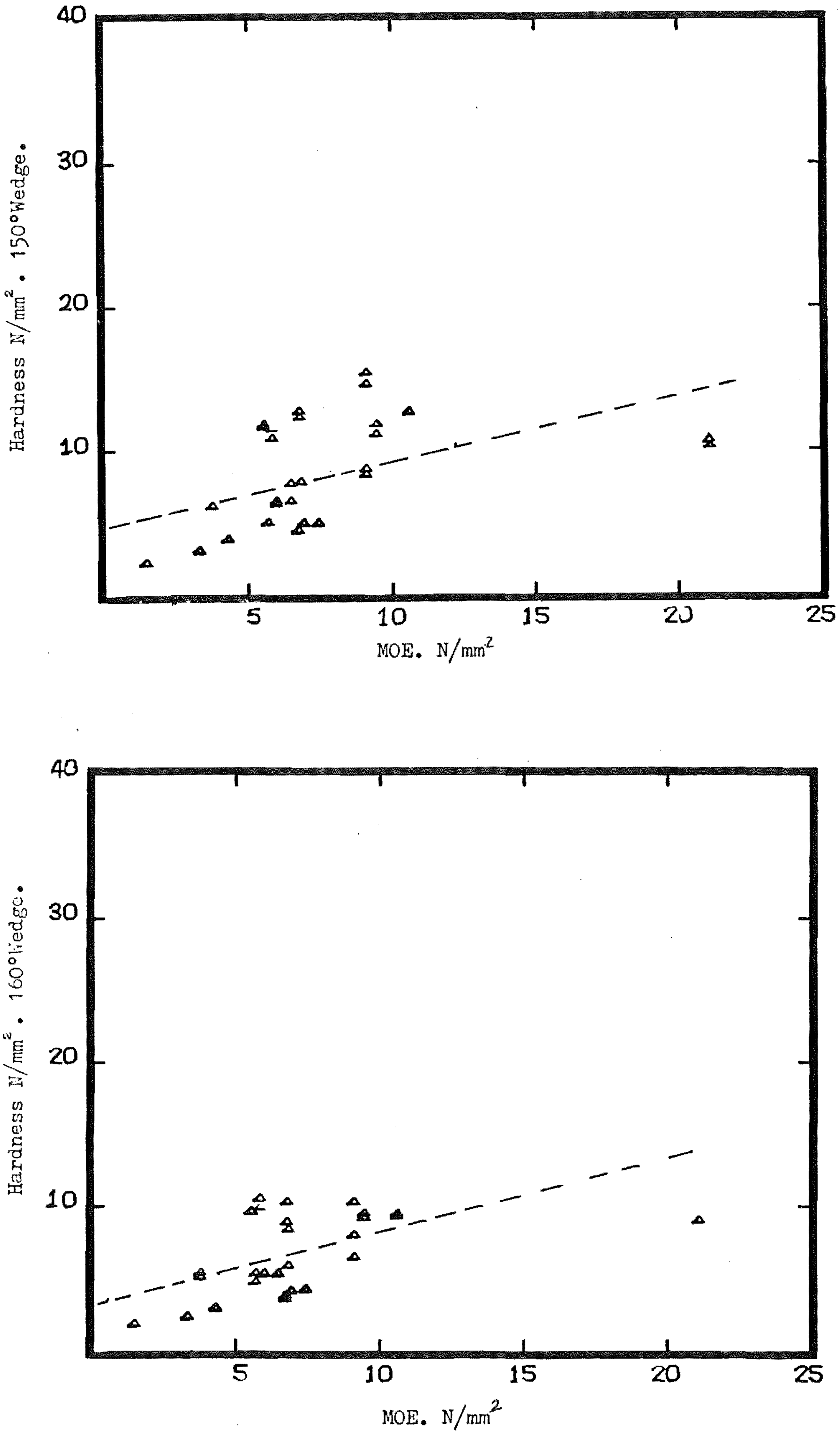


Fig. 36 - (e) and (f) Wedge Hardness versus Modulus of Elasticity in bending for Green Wood.

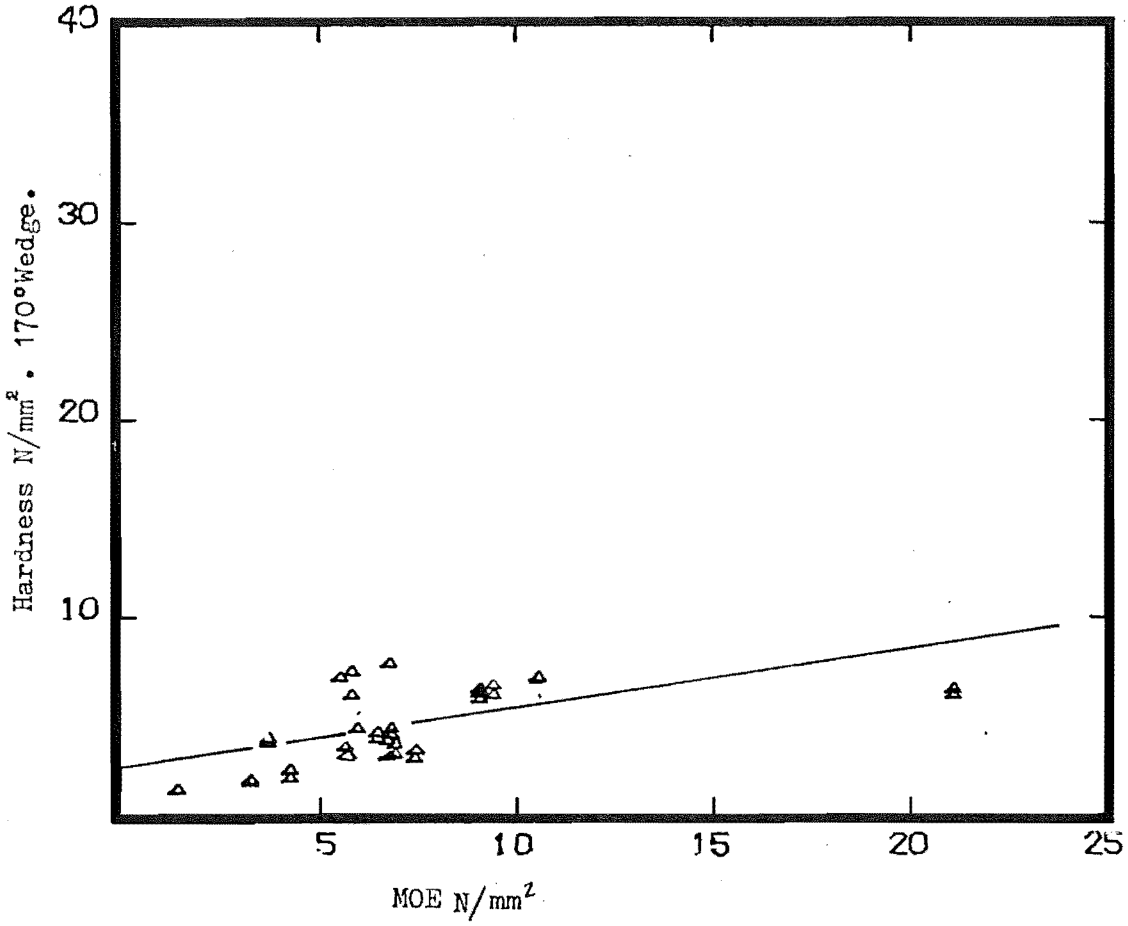


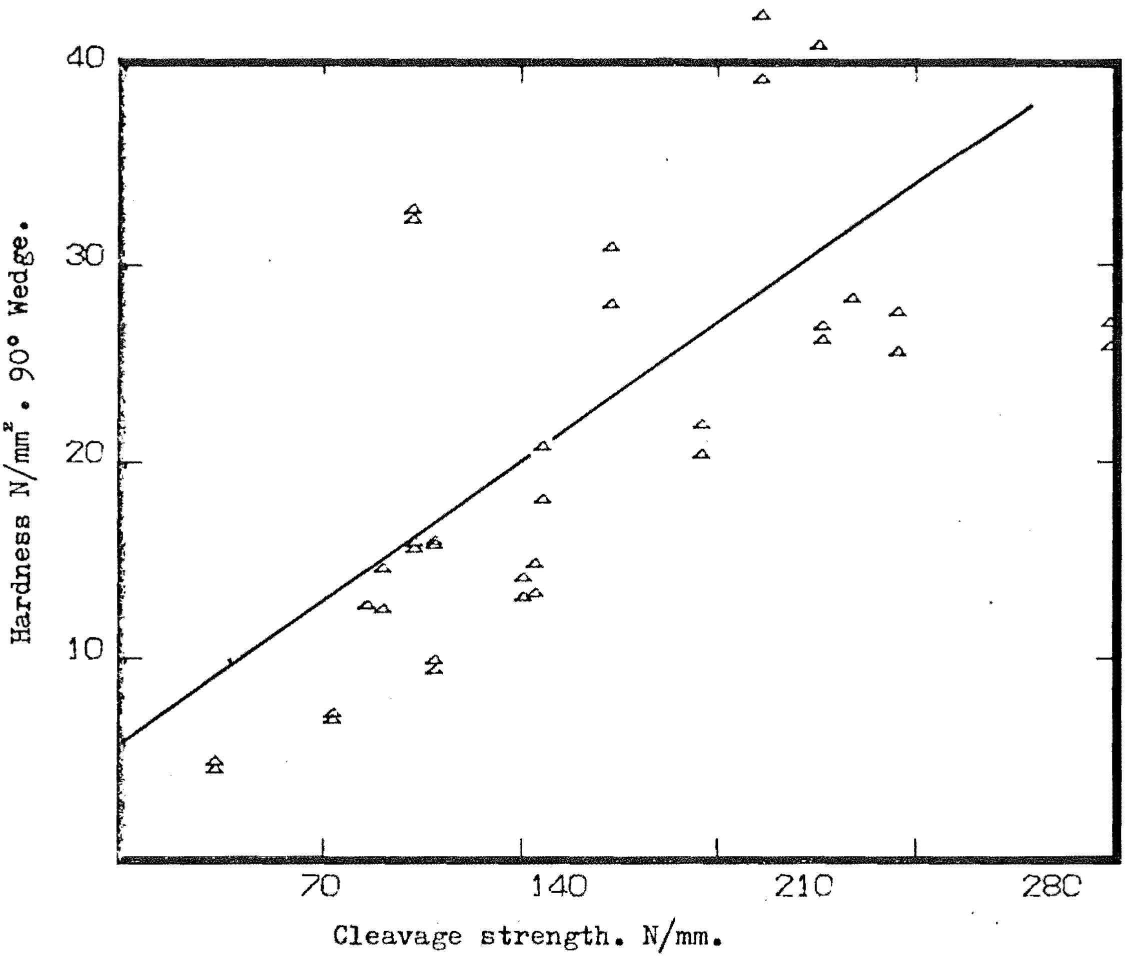
Fig. 36 - (g) Wedge Hardness versus Modulus of Elasticity in bending for Green Wood.

Wedge angle (degrees)	Constant	Coefficient of x	Coefficient of x^2	R^2
Wedge Hardness, H_w, v. Cleavage Strength, σ_{cl}. Green.				
90	6.124	0.111	-	0.4864
105	4.253	0.092	-	0.5269
120	3.457	0.070	-	0.5083
136	2.516	0.056	-	0.5791
150	1.986	0.041	-	0.5451
160	1.709	0.032	-	0.5747
170	1.090	0.022	-	0.5936
90	-5.410	0.313	-0.00069	0.5764
105	-4.275	0.242	-0.00051	0.6039
120	-3.008	0.185	-0.00039	0.5847
136	-2.031	0.136	-0.00027	0.6440
150	-1.708	0.106	-0.00022	0.6187
160	-1.057	0.081	-0.00017	0.6454
170	-0.722	0.055	-0.00011	0.6576
Wedge Hardness, H_w, v. Shear strength parallel to grain, τ. Green.				
90	1.036	2.833	-	0.6195
105	0.632	2.267	-	0.6211
120	0.764	1.725	-	0.6030
136	0.310	1.382	-	0.6839
150	0.079	1.063	-	0.6939
160	0.364	0.811	-	0.6937
170	0.261	0.551	-	0.6754
90	5.068	0.736	0.187	0.6497
105	4.687	0.158	0.188	0.6690
120	3.634	0.232	0.133	0.6432
136	2.823	0.071	0.117	0.7388
150	2.271	-0.077	0.102	0.7650
160	1.527	0.206	0.054	0.7280
170	0.652	0.348	0.018	0.6835

Table 23

Wedge angle (degrees)	Constant	Coefficient of x	Coefficient of x^2	R^2
Wedge Hardness, H_w, v. Cleavage Strength, σ_{cl}. Green.				
90	3.151	0.141	-	0.5665
105	-1.942	0.115	-	0.6007
120	1.701	0.088	-	0.5891
136	1.221	0.069	-	0.6447
150	1.004	0.052	-	0.6102
160	1.103	0.039	-	0.6052
170	0.609	0.028	-	0.6455
90	-2.308	0.247	-0.00042	0.5787
105	-1.369	0.180	-0.00025	0.6077
120	-0.396	0.129	-0.00016	0.5938
136	-0.139	0.096	-0.00010	0.6482
150	-0.553	0.082	-0.00012	0.6181
160	-0.889	0.077	-0.00015	0.6281
170	-0.159	0.043	-0.00006	0.6526
Wedge Hardness, H_w, v. Shear Strength, . Green.				
90	0.808	2.889	-	0.6179
105	0.513	2.296	-	0.6150
120	0.644	1.754	-	0.5991
136	0.262	1.392	-	0.6747
150	0.034	1.074	-	0.6870
160	0.383	0.806	-	0.6788
170	0.262	0.551	-	0.6626
90	5.148	0.599	0.207	0.6543
105	4.741	0.064	0.202	0.6694
120	3.681	0.152	0.145	0.6460
136	2.849	0.027	0.124	0.7354
150	2.296	-0.120	0.108	0.7665
160	1.529	0.201	0.055	0.7147
170	0.654	0.344	0.019	0.6713

Table 24 - Data excluding southern rata



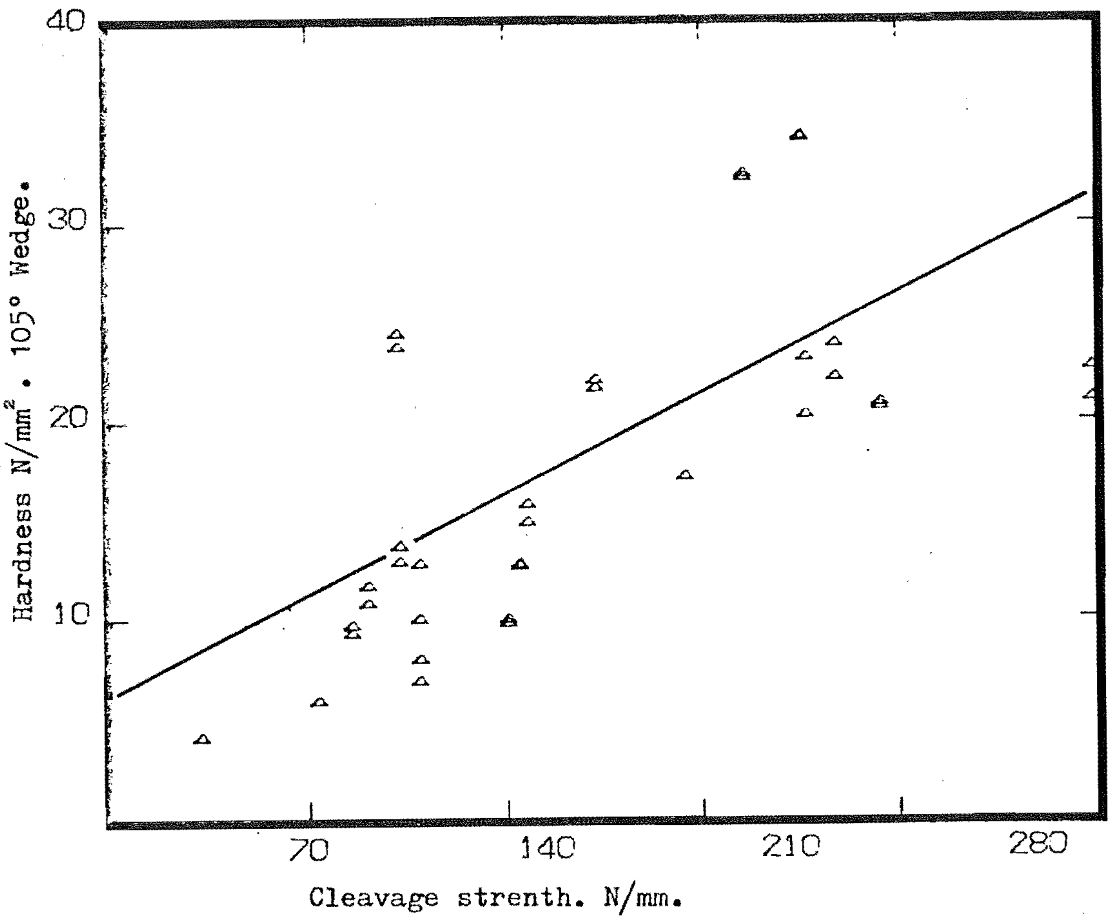
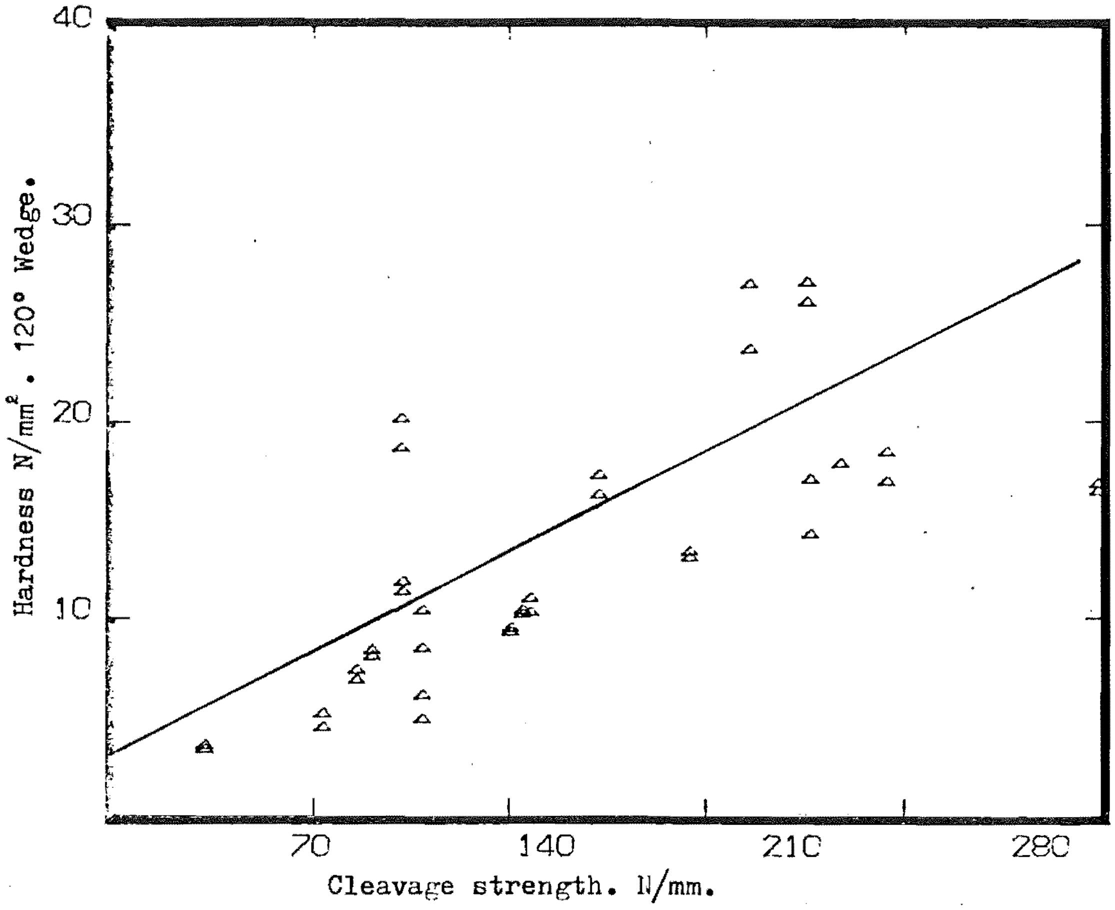


Fig. 37 - (a) and (b) Wedge Hardness versus Cleavage Strength. Green Wood.



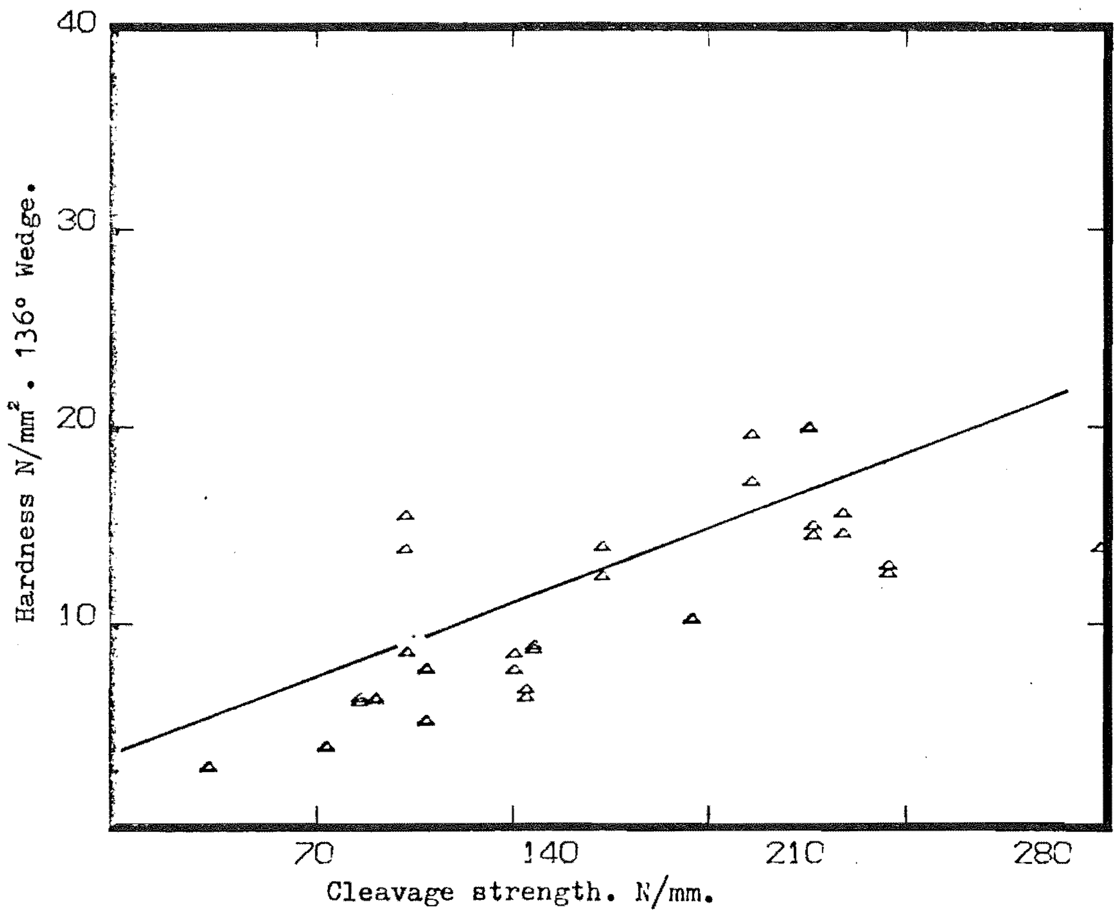
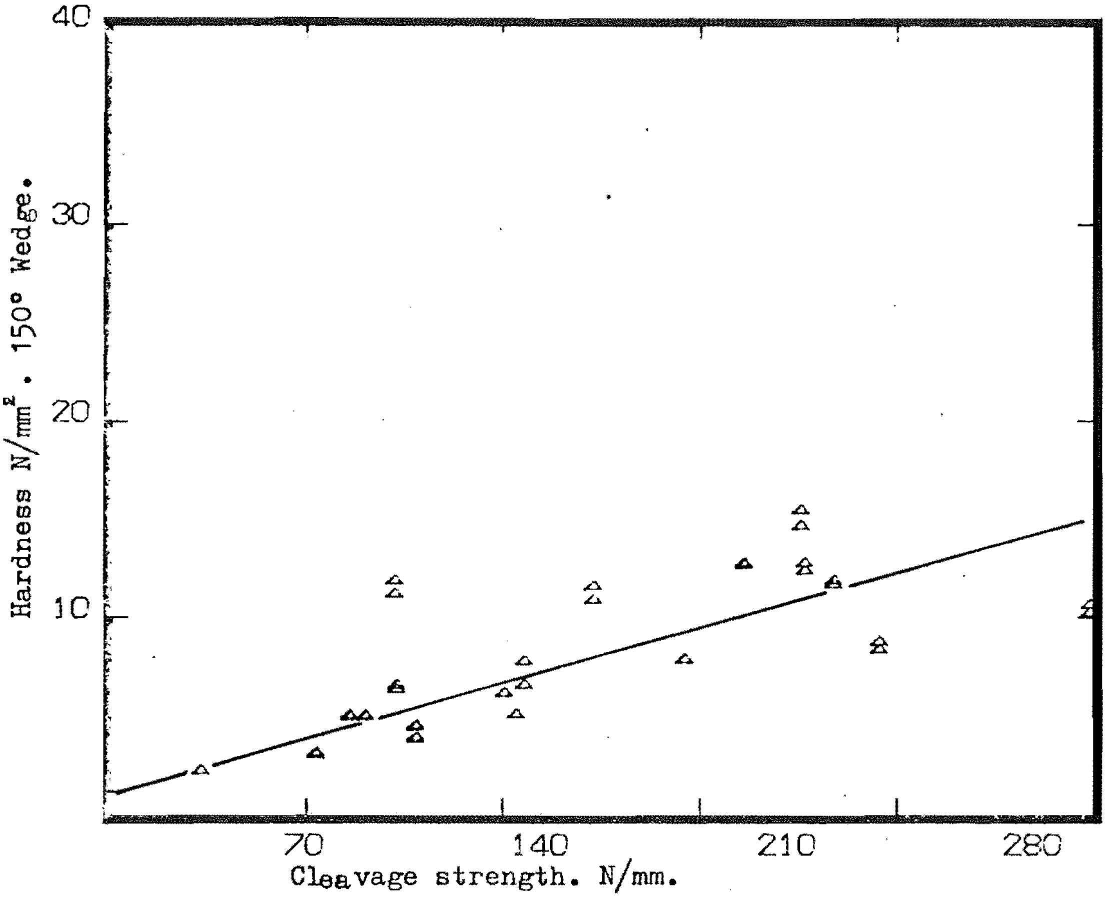


Fig. 37 – (c) and (d) Wedge Hardness versus Cleavage Strength. Green Wood.



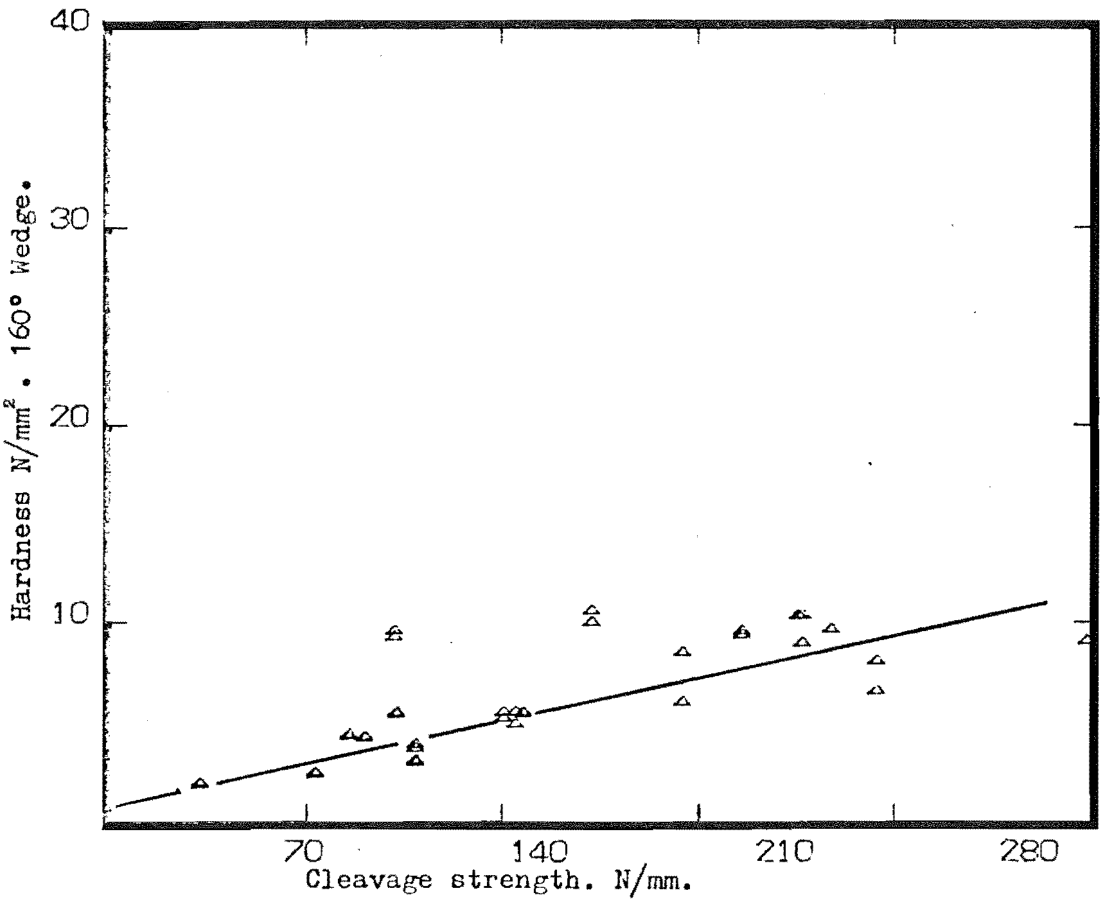


Fig. 37(e) and (f) Wedge Hardness versus Cleavage Strength.
Green Wood.

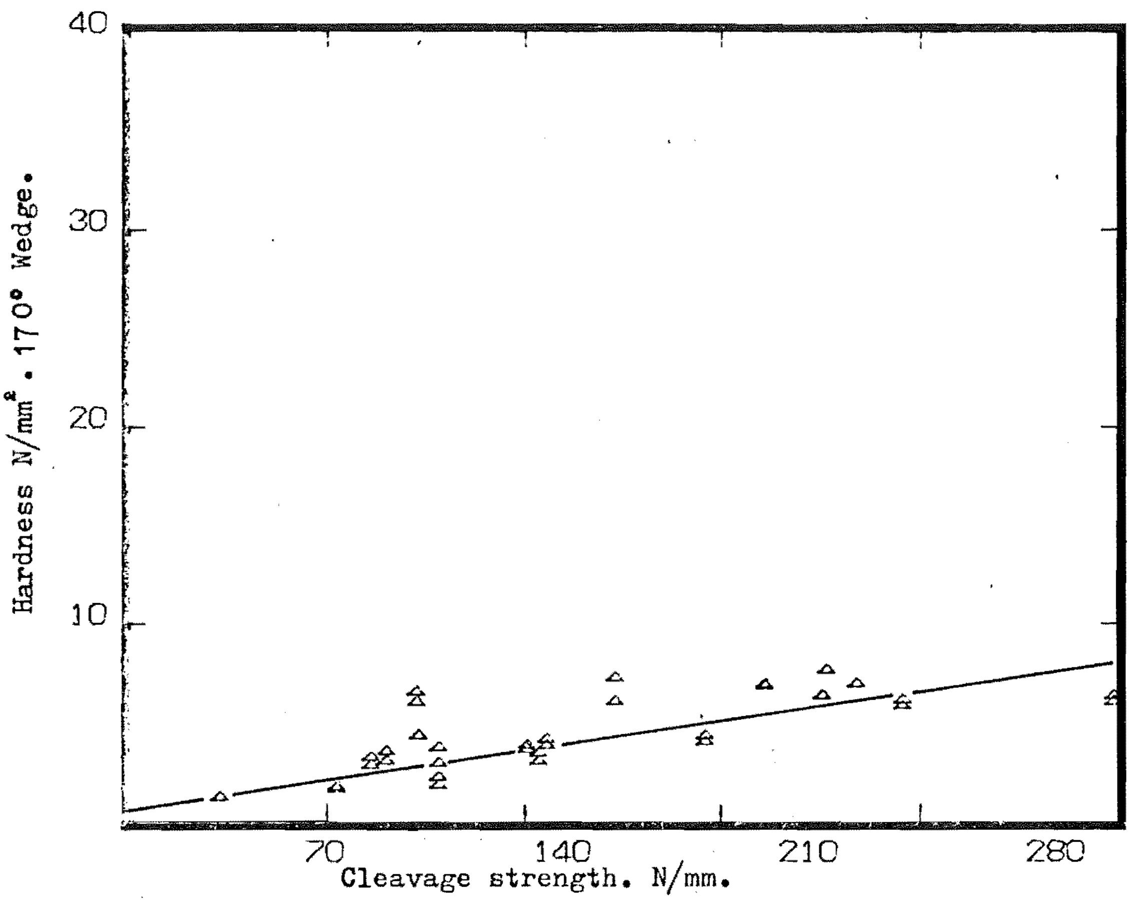


Fig. 37 - (g) Wedge Hardness versus Cleavage Strength. Green Wood.

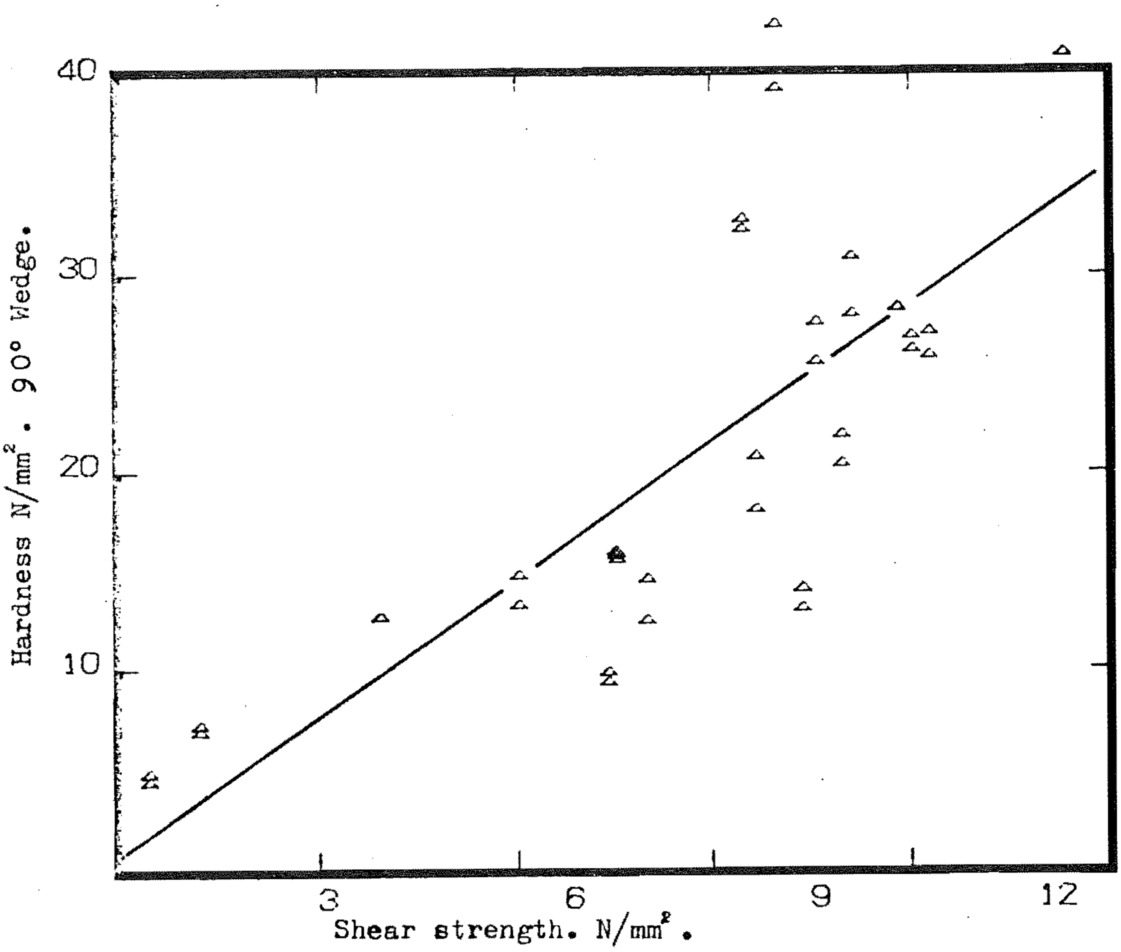
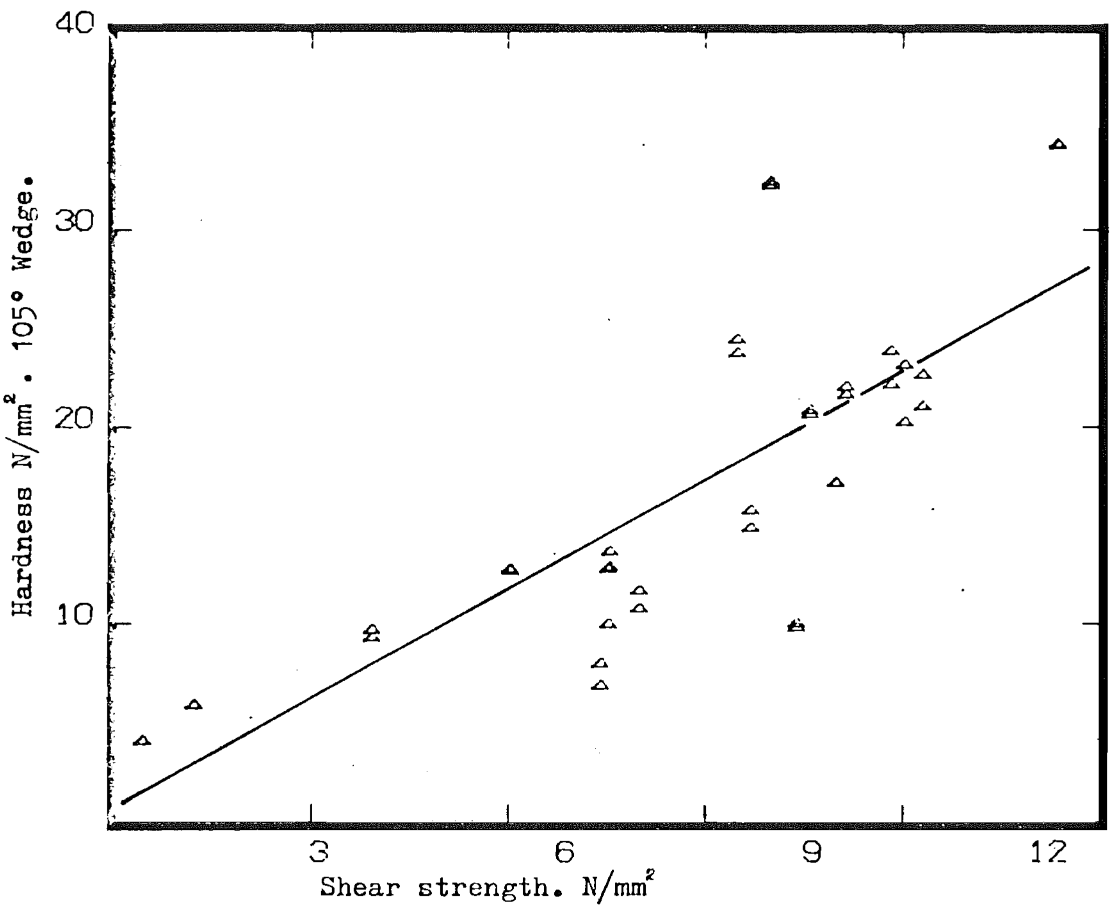


Fig. 38 - (a) Wedge Hardness versus Shear Strength. Green Wood.



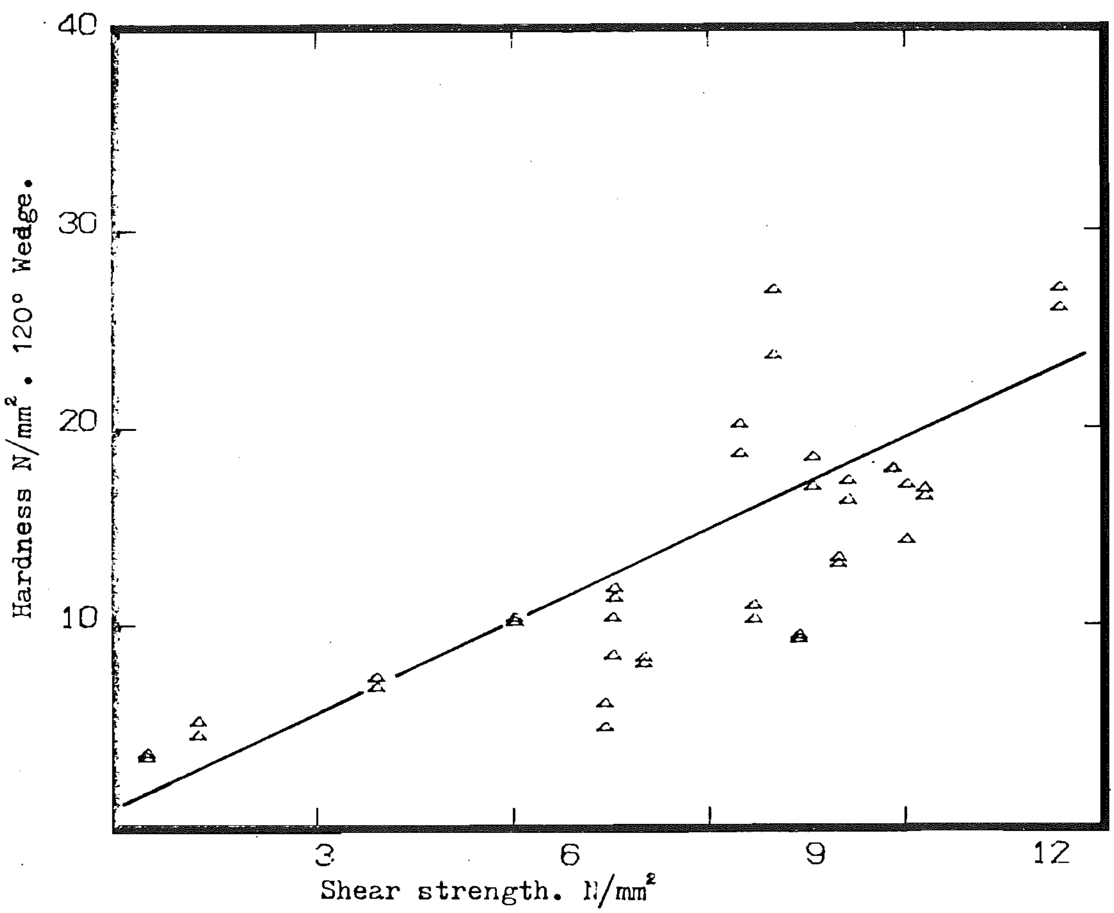
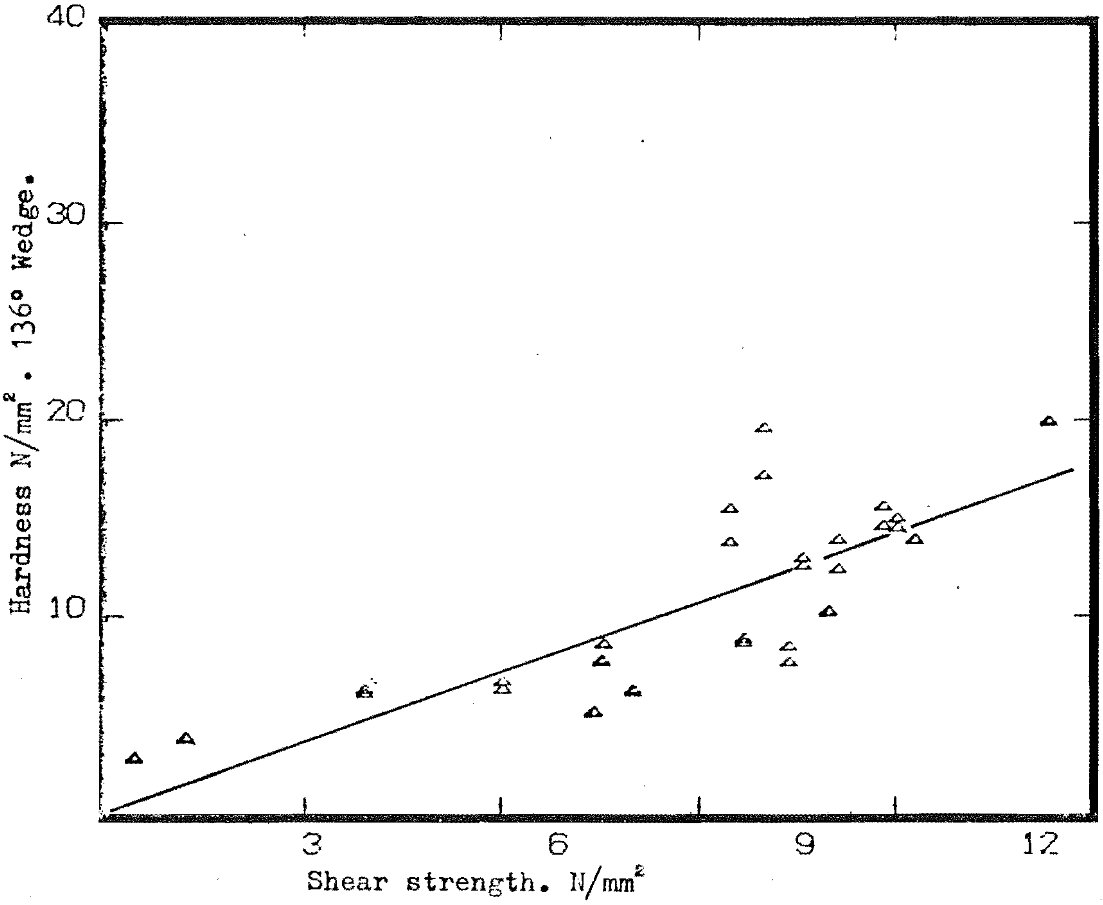


Fig. 38 - (b) and (c) Wedge Hardness versus Shear Strength. Green Wood.



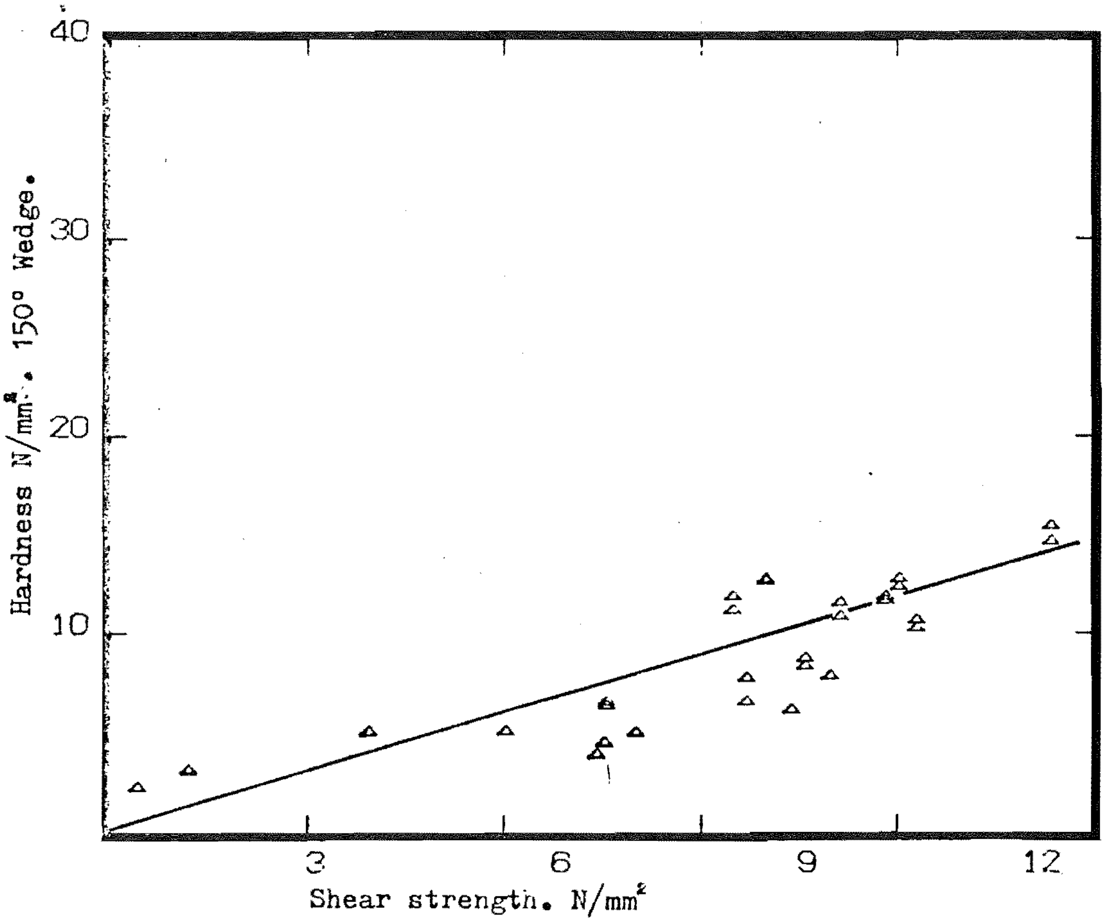
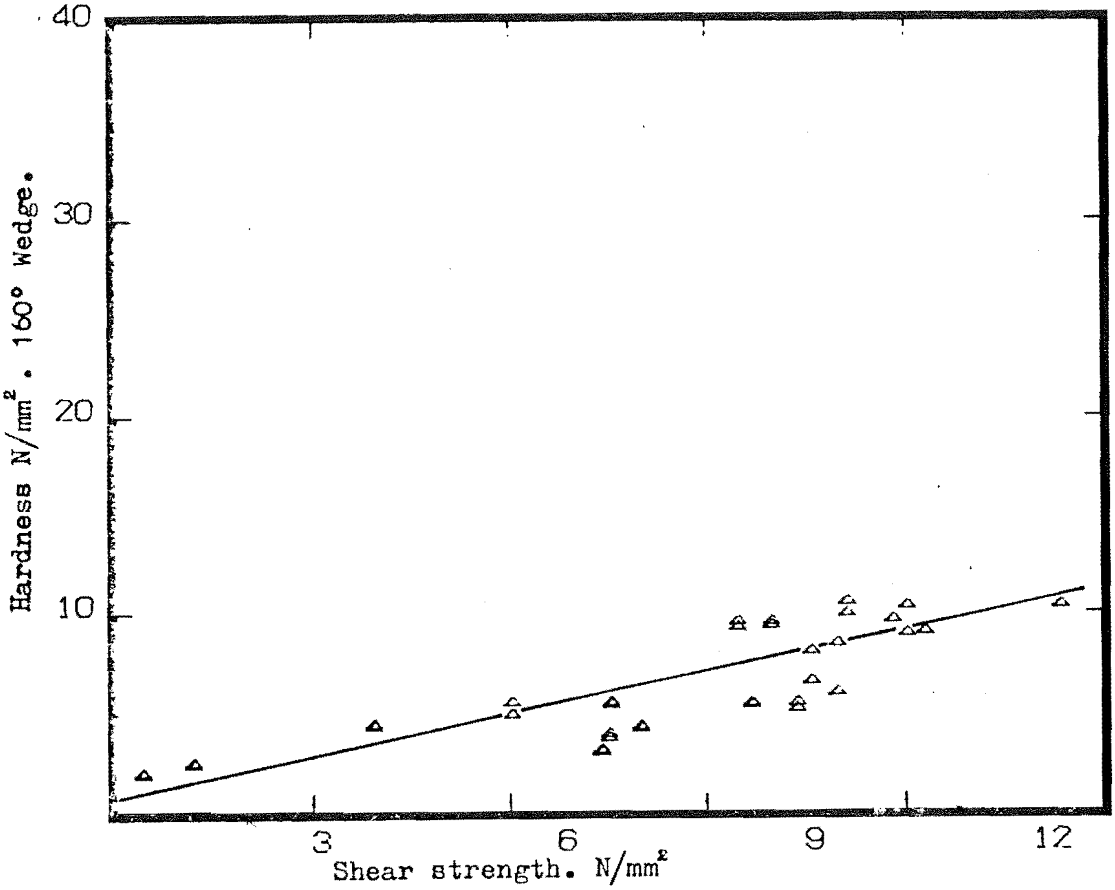


Fig. 38 - (d) and (e) Wedge Hardness versus Shear Strength. Green Wood.



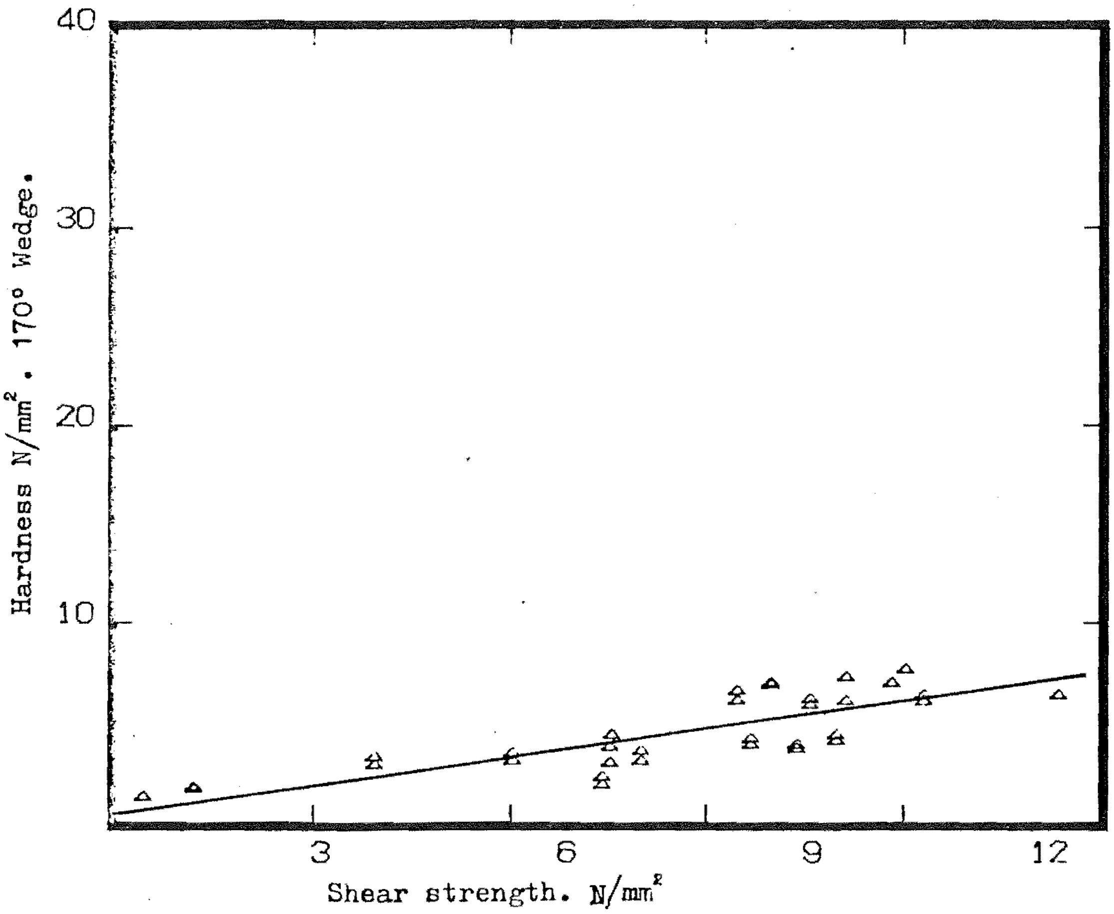


Fig. 38 - (f) and (g) Wedge Hardness versus Shear Strength, Green Wood.

5.3.5 CONCLUSIONS

The aim of this investigation of numerous timbers was to explore the potential of the wedge shaped tool as a convenient guide to the strength and performance of wood in use. The simplicity of the test - a feature shared with other indentation tests such as the Monnin and Janka - makes it very attractive. However, the shortcomings of these other tests have already been discussed and this report serves to highlight the shortcomings and advantages, whichever may be appropriate, of the wedge.

In looking for correlations it must be remembered that certain aspects of the strength properties of wood rely on criteria which may overlap, affecting several characteristics. The categorisation of these characteristics based on simple failure mechanics or precise mathematical analysis is an intractable problem. In both cases, the inhomogeneity, anisotropy and general variability of wood, lead everywhere other than to the point. This should not, however, detract from the valuable results which can be obtained from analysis of correlations such as have been obtained here.

The results of the correlations indicate that the wedge is a valuable tool for investigating the general properties of dry timber. Certainly, the excellent correlation between 136° Wedge Hardness and density ($R^2 = 0.9410$), for example, suggests that Wedge Hardness would be a reliable indicator of any density dependent characteristic. Overall, the wedge test is slightly more reliable than the Janka test as a predictor of density.

With regard to the general strength properties of wood, it is probably optimistic to hope for good correlations between all possible combinations of properties. However, for seasoned wood (12% moisture content) the hardness determined by the wedge shows good reliability in predicting the expected strength of wood as obtained from testing small specimens. In some cases, for example modulus of rupture and modulus of elasticity in bending, Wedge Hardness is a better predictor than density.

An unexpected result is the relationship between compressive strength perpendicular to the grain and Wedge Hardness. Janka Hardness, for example, shows a good linear relationship with compressive strength perpendicular to the grain. However, the blunter indenters particularly do not show an exceptionally good correlation, but the data plots show a reasonable distribution of points (excepting the peculiar characteristic of Mapou).

Both shear strength and cleavage strength are well predicted by Wedge Hardness, the linear relationships in both cases giving good reliability of prediction. Wedge Hardness does not, however, predict shear or cleavage strength quite as reliably as does density.

A most intriguing result of this investigation is the effect which moisture content appears to have on Wedge Hardness. The increased scatter of results might be significantly reduced in a full scale investigation by more extensive sampling. The diverse range of species used in this particular work precluded easy access to unlimited supplies of fresh timber. In all cases except southern rata (for reasons explained earlier), the timber was obtained in the air dry condition. This not only happened to be more practical, but it meant that the wood reached its equilibrium with the environment from the same direction in all cases. This would overcome problems associated with sorption hysteresis. However, the results throw some doubt upon the effectiveness of the soaking procedure used - it is likely that pockets of wood had lower moisture content than that accepted as "green". Sampling of the wood to detect moisture content variability did not show evidence to suggest that the timbers were not completely saturated, but detection of uniform fibre saturation is relatively difficult.

Accepting that considerable work would be necessary to give a clear understanding of the factors affecting the correlations for wet wood, there is still ample confirmation that wedge indentations provide valuable information about wood characteristics. In that the wedge indentation is not an obvious variation of other tests, it is, potentially, a useful, non-destructive assessment method for timbers.

Section D

6. SHARP WEDGES AS A TECHNIQUE FOR DETERMINING THE CLEAVAGE STRENGTH OF WOOD.

Standard cleavage tests are exceedingly time consuming and fiddly operations. The machining of the test sample is the main difficulty even though a machining jig can be easily manufactured. The test piece required by BS373 illustrated in Fig. 39 indicates the amount of work which goes into notching each sample. For this reason - and also out of academic interest - a method of determining cleavage strength using wedges was sought.

The mechanism of failure in cleavage has already been discussed in terms of strain energy and surface energy (Page 133). A similar situation would exist when forcing a sharp wedge into wood samples. Initially, very high stress concentrations would build up at the indenter tip until a crack is formed in the strained material. As the crack deepens, enough strain energy is released from the wood under stress, by relaxing the strain ahead of the crack, to produce new surfaces. Eventually, because of the square law dependency of strain energy released on crack depth (Griffith criteria) and approximately linear dependency of increased surface energy requirement on depth of crack, the wood will split. This point of failure was measured for two wedge indenters, 30^{o} and 45^{o}, in the radial and tangential planes parallel to the grain. Similarly, standard cleavage tests following BS 373 (1957) were also carried out. All the samples were machined 20mm wide so load per millimetre width is one twentieth of the total load required to cause failure. The results of tests on six species - three hardwoods and three softwoods - are shown in Table 26

The most noticeable effect is that with the sharper angle, considerably lower loads are required to produce failure than are required by the 45^{o} indenter. This in turn is much lower than the load reached before failure under the standard test procedure. This is unsurprising, since the stress concentration under a sharp indenter are far higher than those under a less sharp indenter for any given load. It would be expected, even intuitively, that failure would occur more easily under the sharper tool.

The high loads required to cause failure in the standard test sample are likely to be a function of the shape of the sample. Basically, the test is a tensile test across the

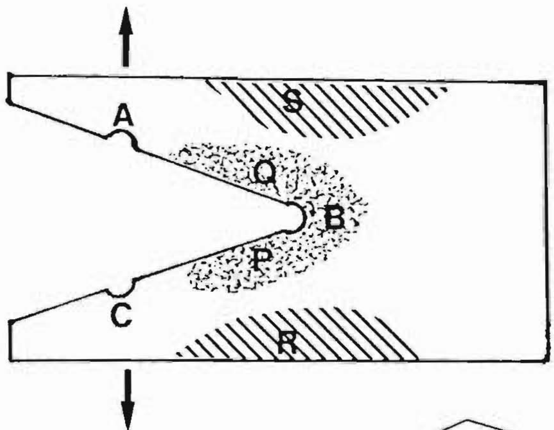


Fig. 39 - Standard Cleavage sample 20 x 20 x 45mm. BS 373 (1957).

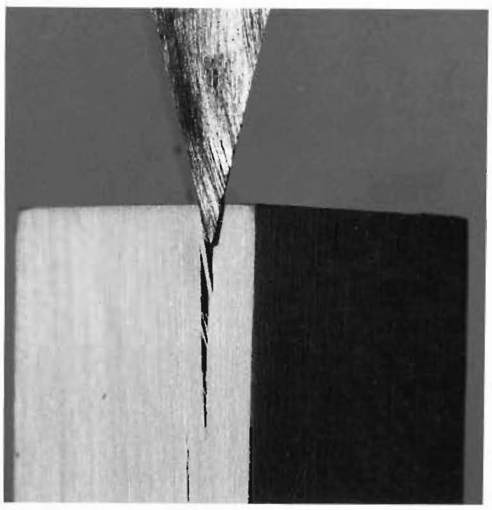


Fig. 40 - Progression of crack ahead of sharp wedge (30^{o}) on kahikatea endgrain.

grain, but application of the load is indirect and influenced by the shape so that a stress concentration is created at the apex of the notch. When a tensile stress is applied at A and C compressive stresses are initiated in the areas R and S and tensile stresses in the areas P and Q. Between these areas will be a region of very high shear stress approximately parallel to the grain where there is zero compressive or tensile stress. The overall effect of this is the storage of a great deal of strain energy in the areas under stress, this store increasing as load and thus strain increases. When failure does occur at the apex, not only is energy released by the normal crack propogation mechanism, but large amounts of stored strain energy in the arms of the sample become available to form surface energy. The new surfaces produced usually require less energy than is available and failure is often accompanied by simultaneous release of audible and kinetic energy.

If the results are reduced to ratios where the lowest value for each test, in this case balsa, is equal to one, it is apparent that the wedges show very nearly equal ratios for a given timber and direction (See Table 25).

	30^{o} Wedge		45^{o} Wedge		Cleavage Strength	
	Radial	Tangential	Radial	Tangential	Radial	Tangential
Balsa	1.00	1.00	1.00	1.00	1.00	1.00
P. strobus	10.25	7.44	10.18	7.18	1.82	1.67
Kahikatea	12.32	8.07	21.18	13.06	2.26	2.33
Tawa	25.74	20.08	25.16	18.72	5.48	4.68
Douglas fir	20.67	16.02	20.57	15.87	3.48	3.08
European beech	20.16	21.66	22.25	18.97	6.13	6.81

Table 25 - 30^{o}, 45^{o} and BS Standard Cleavage values as a ratio of the lowest value.

The ratios for the standard cleavage test are consistent in agreement between radial and tangential directions, but show a greatly reduced range. This is an indication that the standard test as carried out may be less sensitive to changes in "cleavage strength" because, in effect, compressive, tensile and shear factors are much more involved than in the wedge test. This tends to have a damping effect on the range of cleavage strength values obtained by the standard method.

The graph in Fig. 41 shows the relationship between cleavage strength measured by the wedge methods and standard cleavage strength. It is apparent from this that the Wedge test is more sensitive to changes at lower strength values and the standard test is more sensitive at the high strength values. The dip in the centre of the 45^{o} radial curve and at the last point on the 30^{o} radial curve are indications of the weakness of Douglas fir in cleavage in this direction when split by a wedge. The final drop in the 45^{o} radial curve is caused by European beech - possibly an indication of the well developed multiseriate ray pattern characteristic of this timber.

Although this investigation is intended to show the possibility of using wedges in an alternative cleavage test, the results are very encouraging. In the standard test, the storage of energy by the methods discussed above serve to provide a diffuse stress area rather than a stress concentration. Thus considerably more work needs to be done to produce a failure than is necessary. The standard test might aptly be re-named "The force required to cause cleavage failure, lots of noise and pieces of flying wood" since this is really what is being measured. On these grounds and considering the time consuming method of sample preparation, the wedge cleavage test using either of the sharp angles is worthy of thorough investigation.

	30° Wedge		45° Wedge		Cleavage Strength	
	Radial	Tangential	Radial	Tangential	Radial	Tangential
Balsa	1.78 (0.1)	2.52 (2.2)	2.75 (1.3)	4.07 (6.8)	32.50 (24.0)	36.00 (7.8)
P. strobus	18.25 (3.9)	18.76 (11.7)	27.99 (2.5)	29.22 (1.0)	59.10 (3.5)	60.14 (4.8)
Kahikatea	21.94 (0.4)	20.33 (12.7)	58.26 (9.3)	53.17 (6.4)	73.50 (12.5)	83.75 (6.3)
Tawa	45.81 (8.3)	50.60 (3.0)	69.20 (3.8)	76.21 (0.1)	178.00 (4.2)	175.00 (14.1)
Douglas fir	36.80 (16.8)	40.38 (16.0)	56.58 (7.1)	64.59 (6.0)	113.25 (8.4)	111.50 (29.0)
European beech	35.89 (10.7)	54.58 (4.2)	61.19 (12.6)	77.23 (10.1)	199.25 (11.2)	245.00 (4.3)

Table 26 - 30° and 45° wedge indentations on endgrain of 20 x 20 x 25mm samples of selected timbers. Cleavage standard to BS 373. Figures in N/mm.

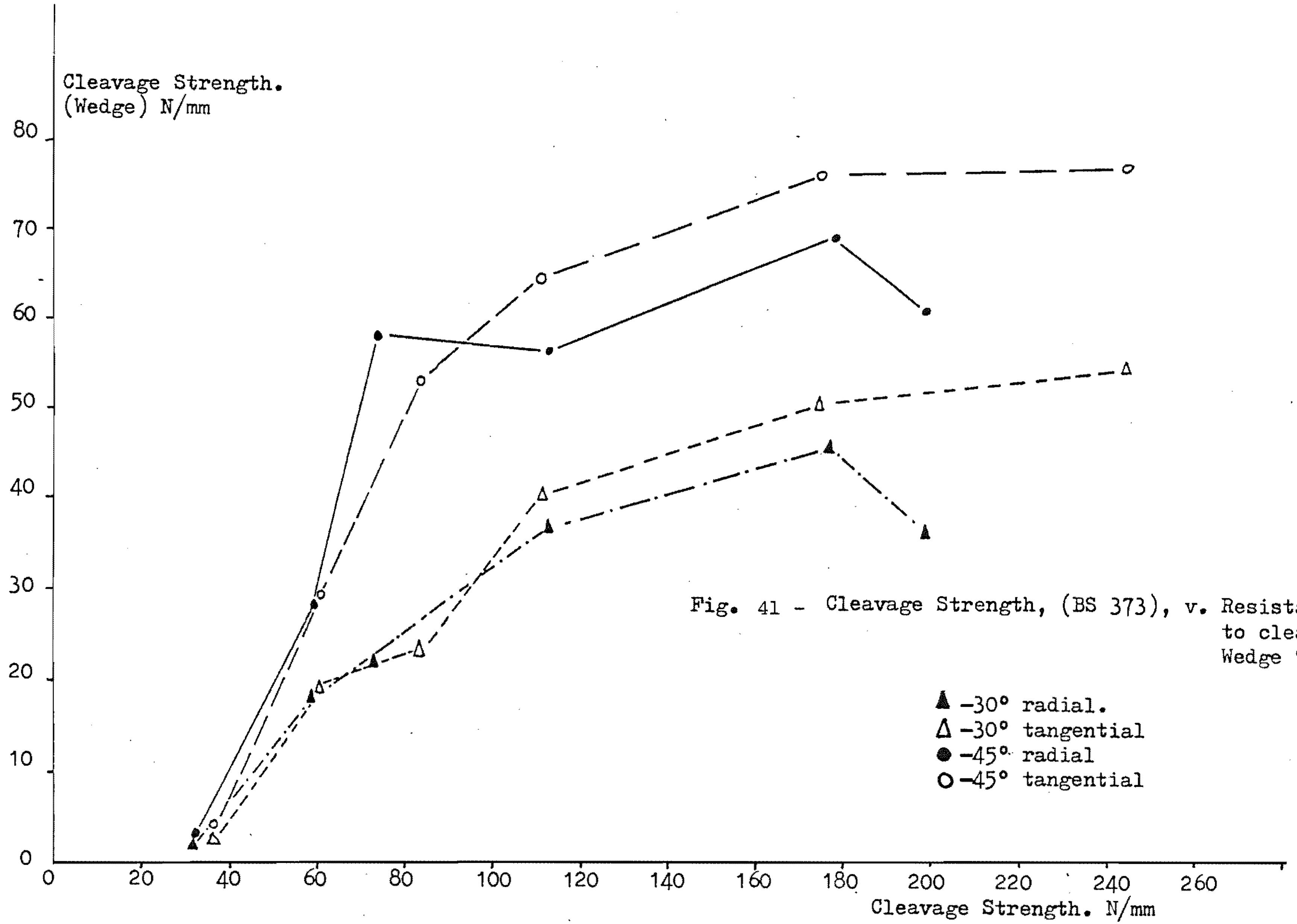


Fig. 41 - Cleavage Strength, (BS 373), v. Resistance to cleavage by Wedge Tools.

7. INDENTATION OF WOOD BASED BOARD PRODUCTS - A Preliminary Investigation.

A series of exploratory tests was done with a view to extending the Wedge Hardness test to particle board and fibreboard.

Messrs Fletchers Particleboard kindly provided samples of 9mm, 12mm, 15mm and 18mm interior grade board and an 18mm exterior grade board. Samples were also obtained of Customwood 12mm and 18mm fibreboard.

7.1 Experimental Procedure

Conditioned samples were machined to 20mm wide strips for indentation with a 136° wedge and Janka ball tests were carried out on the board faces well away from the edges. Relative humidity and temperature at the time of testing were 55% and 20°C respectively.

Only two Janka tests and two 136° wedge tests were carried out on each sample surface to give an idea of the effect - more would be needed to give a fair assessment of the boards. Plots of the means for each of the seven boards are shown in Fig. 43. Results are given in Tables 27 and 28.

Apart from the 9mm board which shows an exceedingly high Janka hardness, the points do show a reasonable relationship considering the minimal data generated. It is likely that with the 9mm board the ball is compressing the board into the surface below, in this case the steel plate on the load cell. Placing a similar piece of board underneath would be of little help as this would compress by an amount dependent on its least dense layer. This board is simply too thin to be tested by the Janka method.

All the Wedge Hardness values are computed at 1kN load, though this is not critical as the load/penetration curve is linear over the whole duration of the test. The load increase tended to become progressively slower with penetration for the Janka tests, particularly towards the end of the test.

The value of the wedge test was not, however, seen as being a test for surface hardness, but as a test of hardness gradient across the board. In order to investigate this, the 20mm sticks were scarfed at 25° so that indentations could be made easily into the edge of the boards. Readings of hardness were then made on the edge near the face at A, in the centre at C and in an intermediate position B for the thicker boards. See Fig. 42.

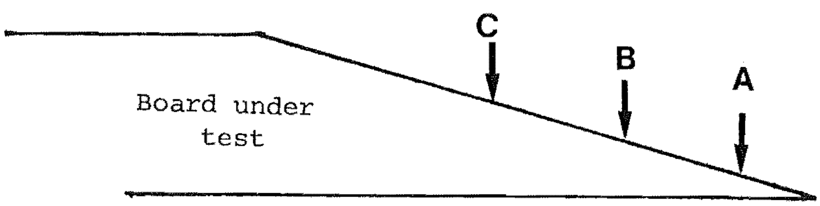


Fig. 42 - Scarfed edge of board products for testing with 136° Wedge.

The results were less than encouraging. Occasionally a trend across the board could be detected, but more often than not, the figures appear to show no order whatsoever. It may be that layers underlying the test area have a large effect on the results using this test sample configuration.

The fibreboards proved to be slightly more consistent than the particle boards in tests results across the scarfed face. This type of board is generally more homogeneous than particleboard as there is no variation in particle size within the board.

The bonding between particles is obviously of some importance here and a test method as crude as an indenter could not pick out the subtle variations in internal bond strength. A major study would be needed to correlate the internal bond strength with indentation hardness which is beyond the scope of the present investigation.

The results show that the 136^{o} Wedge is as reasonable an indicator of hardness as is the Janka ball, though the wedge may be more suited to thinner boards. One drawback of the wedge is the necessity of producing samples approximately 20mm wide for testing. Whereas the Janka test can satisfactorily be carried out on the board surface for any size of sample, the wedge would be influenced by edge shear effects if the sample were wider than the test tool. This may indicate that a cone shaped tool be worthy of investigation ..... see Kumichel and Holz (1955) and Nedbal (1956).

Particle Board	136^{o} Wedge Hardness N/mm^2	Mean	Coefficient of variation	Janka Hardness N/mm^2	Mean	Coefficient of variation
9mm	17.57	16.00	(13.9)	84.0	8.0	(4.1)
	14.43			89.0		
12mm	14.43	13.33	(11.6)	39.0	37.5	(5.7)
	12.24			36.0		
15mm	8.98	9.19	(3.0)	28.0	30.0	(9.4)
	9.39			32.0		
18mm	13.93	14.74	(7.7)	36.0	36.5	(5.0)
	15.54			37.0		
18mm ext.	13.93			36.0	38.5	(9.2)
	13.47	13.71	(2.3)	41.0		
Fibreboard						
12mm	16.83	(16.83)	(0.0)	46.0	46.0	(0.0)
	16.83			46.0		
18mm	18.37	18.37	(0.0)	46.0	44.5	(4.8)
	18.37			43.0		

Table 27 - Hardness of board products tested by Janka method and using 136^{o} Wedge tool.

Board	Wedge Hardness at A	Wedge Hardness at B	Wedge Hardness at C
Particle Board 9mm	8.23	-	9.32
	9.72	-	3.53
Particle Board 12mm	5.51	-	6.54
	6.93	-	4.73
Particle Board 15mm	11.05	8.55	5.96
	6.08	5.19	6.41
Particle Board 18mm	9.54	8.69	6.29
	4.77	7.04	5.93
Particle Board 18mm	6.99	5.21	5.26
(exterior)	6.71	7.52	5.74
Fibreboard 12mm	12.77	-	11.30
	16.32	-	14.69
Fibreboard 18mm	18.69	15.52	11.10
	16.19	13.16	13.30

Table 28 - Wedge Hardness measured across the scarfed edge of boards (See Fig. 42).

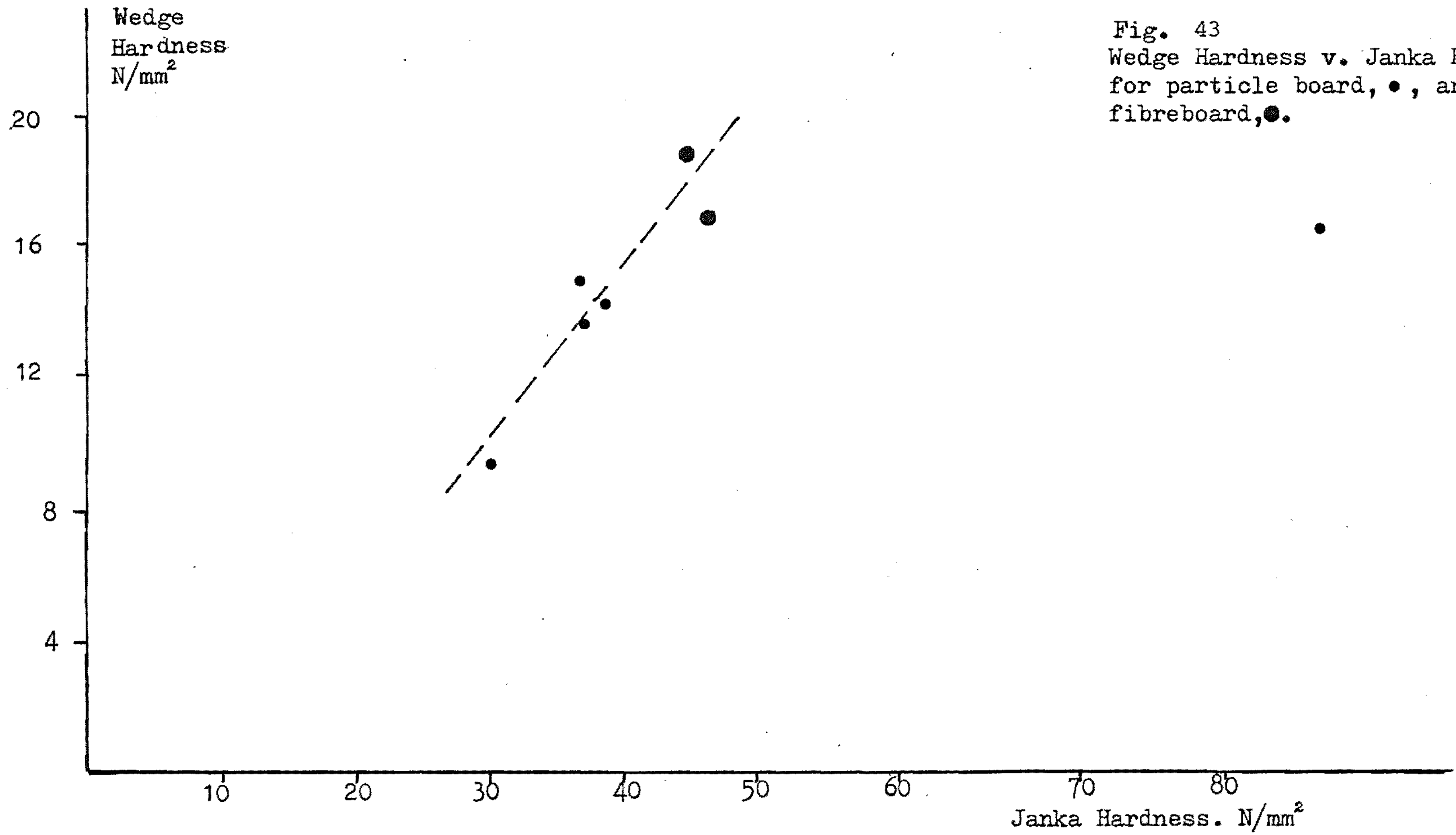


Fig. 43
Wedge Hardness v. Janka Hardness for particle board, ● , and fibreboard, ⬤.

Section E

SUMMARY

Hardness testing of wood developed originally from work relating to metals. Though test methods in metallurgy have been improved and diversified since their origins around 1900, the hardness testing of wood, though thoroughly investigated has not significantly developed. The main reason for this situation has been a certain preoccupation with aspects of ball indentation rather than a more fundamental question concerning the mechanisms involved in indentations using the spherical tool.

The results of tests carried out in this report indicate the following:

(a) Present hardness tests have several shortcomings which may be overcome by use of a wedge tool. The Janka test is convenient and easy to perform, but penetration depth seems excessive. The Monnin test is difficult to perform accurately and is based on inconsistent reasoning. The wedge tool is easy to use, gives reliable results and is based on easily interpreted Meyer Hardness (load/projected area).

(b) Wood behaves as a range of materials, the spectrum embracing low density cellular materials and heavy, almost solid woods such as southern rata. Characteristics of low density foams can be attributed to woods such as balsa, whereas southern rata behaves in many cases almost as a rigid-plastic solid.

(c) Wood can be categorised using the parameter Wedge Hardness. The correlations are excellent for air dry wood

(moisture content 12%), especially with density. Relationships involving green woods show weaker correlations, but still reliably indicate the strength properties of wood.

(d) Sharp wedges may be more indicative of the resistance of wood to cleavage parallel to the grain than present tests used to measure this property. The wedges are more sensitive to density changes giving a wider range of comparative cleavage strength values than the standard test.

(e) It does not appear likely that Wedge Hardness tests would furnish more information from board products than would a standard Janka test. The fact that the Wedge test requires machining of samples whereas the Janka test does not, means that the Janka test would normally be more convenient than the Wedge test. However, the wedge may be a more useful tool for determining the hardness of thin boards since the penetration depth required to provide a hardness reading is very low indeed. The measurement of hardness variations across the edge of a board scarfed to a low angle did not show reliable results, though it would be worthwhile persuing this approach if something was known about the variations in internal bond strength of the materials under test.

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Appendices

APPENDIX A

EFFECT OF LOADING RATE ON HARDNESS

The analysis of variance breaks down the effects and considers the different treatments as follows:

Variable 1 - Wedge Hardness

Variable 2, Bo - intercept on the hardness (y) axis

Variable 3, SPD - the effect of different speeds of indentation, in this case 0.01, 0.1, 0.5, 1.0 and 5.0mm/min.

Variable 4, ANGLE - included angle of indenters used in this case 90^o, 105^o, 120^o, 136^o, 150^o, 160^o and 170^o.

Variable 5, SPDXAN - interaction between speed and angle effects.

Variable 6, SPDSQ - effect of square of speed.

In the final equation, obtained at Step 5 of the computation, all the above variables are entered and each one shows a significant effect on hardness. The most significant effect is that of angle - a linear regression of the form

$$y = \alpha_1 + \alpha_2\beta$$

(where y is hardness, α_1 is a constant B_o, α_2 is the coefficient of the angle β) describes 95.5% of the variation in hardness (see Summary Table A).

The significant square of speed term, which is negative, indicates that, as hardness increases, the effect of speed decreases. The negative interaction term, which is the least significant of the variables, but still has an effect, suggests that as both speed and angle increase, interaction of the two act to limit the increase in hardness.

In summary, the effect of angle and speed are most significant and the following equation for hardness (y).

$$y = B_o + \alpha_1 S + \alpha_2 \beta \qquad \begin{aligned} S &= \text{speed} \\ \beta &= \text{angle} \\ \alpha_1, \alpha_2 &= \text{constants} \end{aligned}$$

accounts for 98.32% of the variability of the Wedge hardness.

A

SUB-PROBLEM 1

DEPENDENT VARIABLE	1
MAXIMUM NUMBER OF STEPS	10
F-LEVEL FOR INCLUSION	0.010000
F-LEVEL FOR DELETION	0.005000
TOLERANCE LEVEL	0.001000

STEP NUMBER 1
VARIABLE ENTERED 4

MULTIPLE R	0.8106
STD. ERROR OF EST.	9.0102

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	1	21622.970	21622.970	266.344
RESIDUAL	139	11284.628	81.184	

VARIABLES IN EQUATION

VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE
(CONSTANT	0.00000)		
ANGLE 4	0.09154	0.00561	266.3440 (9)

VARIABLES NOT IN EQUATION

VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
BO 2	0.96318	0.0403	1771.3017 (8)
SPD 3	0.26639	0.6806	12.3297 (9)
SPDXAN 5	0.13685	0.6672	2.6340 (8)
SPDSQ 6	0.23433	0.7666	8.0182 (7)
ANSQ 7	-0.93192	0.0281	911.1895 (7)

STEP NUMBER 2
VARIABLE ENTERED 3

MULTIPLE R	0.8278
STD. ERROR OF EST.	8.6641

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	2	22548.510	11274.255	150.192
RESIDUAL	138	10359.089	75.066	

VARIABLES IN EQUATION

VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE
(CONSTANT	0.00000)		
SPD 3	1.35991	0.38729	12.3297 (9)
ANGLE 4	0.07857	0.00654	144.4288 (9)

VARIABLES NOT IN EQUATION

VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
BO 2	0.97297	0.0395	2432.0128 (8)
SPDXAN 5	-0.60457	0.0395	78.9214 (8)
SPDSQ 6	-0.32627	0.0168	16.5460 (7)
ANSQ 7	-0.94041	0.0275	1047.7373 (7)

STEP NUMBER 3
VARIABLE ENTERED 2

MULTIPLE R	0.9916
STD. ERROR OF EST.	2.0081

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	3	32355.170	10785.057	2674.651
RESIDUAL	137	552.428	4.032	

VARIABLES IN EQUATION

VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE

VARIABLES NOT IN EQUATION

VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER

A

(CONSTANT	0.00000)				VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
BD 2	42.11418	0.85398	2432.0128 (8)		SPDXAN 5	-0.28728	0.0269	12.2333 (8)
SPD 3	0.73245	0.09066	65.2723 (9)		SPDSQ 6	-0.53708	0.0180	55.1335 (7)
ANGLE 4	-0.21934	0.00623	1240.3301 (9)		ANSQ 7	0.37620	0.0009	22.7002 (7)

STEP NUMBER 4
VARIABLE ENTERED 5

MULTIPLE R 0.9923
STD. ERROR OF EST. 1.9305

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	4	32400.760	8100.190	2173.528
RESIDUAL	136	506.638	3.727	

VARIABLES IN EQUATION					VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE		VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)							
BD 2	40.14727	0.99512	1627.6664 (8)		SPDSQ 6	-0.56072	0.0180	61.9085 (7)
SPD 3	2.22027	0.43422	26.1452 (9)		ANSQ 7	0.39485	0.0009	24.9345 (7)
ANGLE 4	-0.20455	0.00733	778.7708 (9)					
SPDXAN 5	-0.01119	0.00320	12.2333 (8)					

STEP NUMBER 5
VARIABLE ENTERED 6

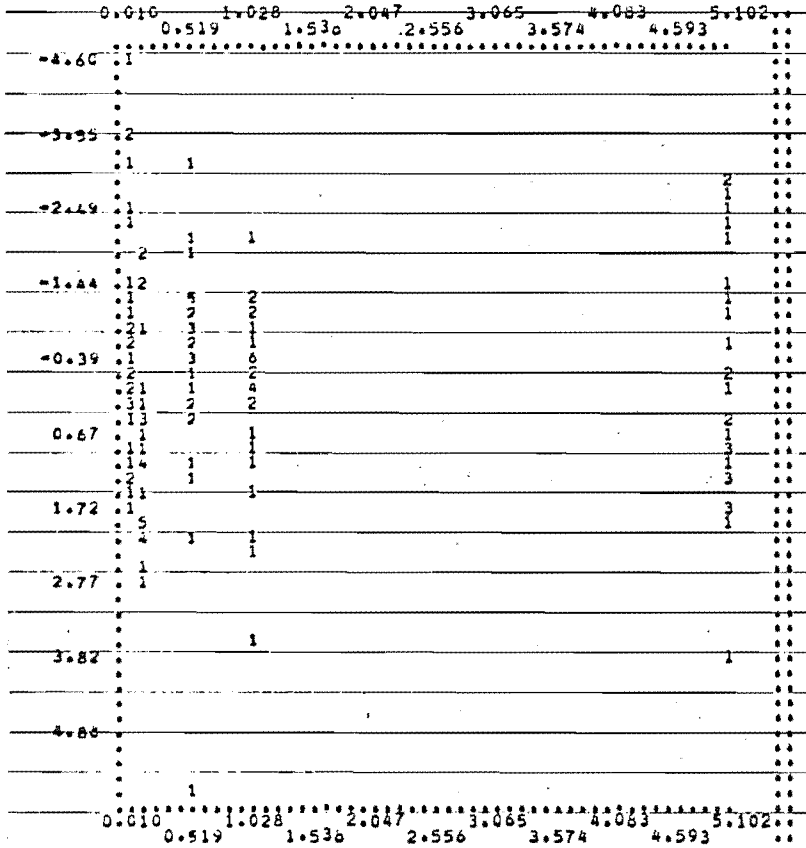
MULTIPLE R 0.9947
STD. ERROR OF EST. 1.6044

ANALYSIS OF VARIANCE

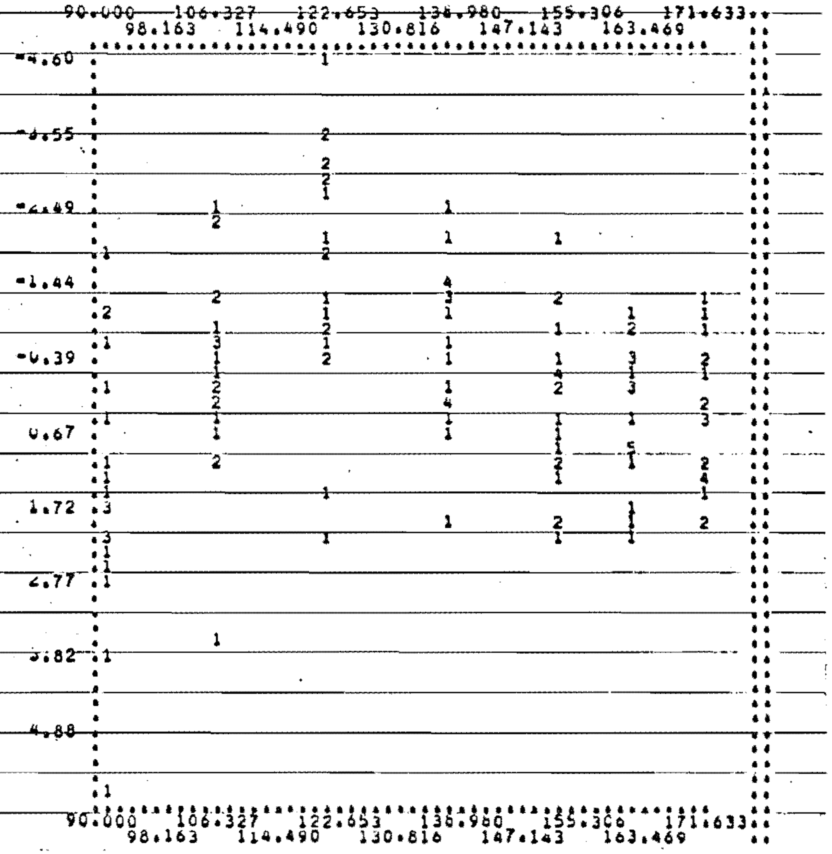
	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	5	32560.111	6512.022	2529.947
RESIDUAL	135	347.487	2.574	

VARIABLES IN EQUATION					VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE		VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)							
BD 2	38.97790	0.84026	2151.8490 (8)		ANSQ 7	0.47686	0.0009	39.4402 (7)
SPD 3	5.92925	0.59366	99.7525 (9)					
ANGLE 4	-0.20455	0.00609	1127.5485 (9)					
SPDXAN 5	-0.01119	0.00266	17.7121 (8)					
SPDSQ 6	-0.71094	0.09036	61.9085 (7)					

PLOT OF RESIDUALS (Y-AXIS)
VS. VARIABLE 3 (X-AXIS)



PLOT OF RESIDUALS (Y-AXIS)
VS. VARIABLE 4 (X-AXIS)



SUMMARY TABLE A

STEP NUMBER	VARIABLE ENTERED	VARIABLE REMOVED	MULTIPLE R	MULTIPLE RSQ	INCREASE IN RSQ	F VALUE TO ENTER OR REMOVE	NUMBER OF INDEPENDENT VARIABLES INCLUDED
1	ANGLE 4		0.8106	0.6571	0.6571	286.3440	1
2	SPV 3		0.8278	0.6852	0.0281	12.3297	2
3	BU 2		0.9916	0.9832	0.2980	2432.0128	3
4	SPDXAN 5		0.9923	0.9846	0.0014	12.2333	4
5	SPDSQ 6		0.9947	0.9894	0.0048	61.9065	5

B

```
SUB-PROBLEM      1
 DEPENDENT VARIABLE              1
 MAXIMUM NUMBER OF STEPS        10
 F-LEVEL FOR INCLUSION     0.010000
 F-LEVEL FOR DELETION      0.005000
 TOLERANCE LEVEL           0.001000
```

```
STEP NUMBER      1
VARIABLE ENTERED      3

MULTIPLE R              0.8442
STD. ERROR OF EST.      5.5435

ANALYSIS OF VARIANCE
                      DF    SUM OF SQUARES    MEAN SQUARE    F RATIO
      REGRESSION       1       12727.022       12727.022     414.148
      RESIDUAL       167        5132.007          30.731

               VARIABLES IN EQUATION                  :                  VARIABLES NOT IN EQUATION
  VARIABLE      COEFFICIENT  STD. ERROR  F TO REMOVE  :     VARIABLE    PARTIAL CORR.    TOLERANCE    F TO ENTER
                                                      :
  (CONSTANT       0.00000 )                           :
   RHO   3        0.01123     0.00055    414.1485 (9) :      BO     2     -0.31440        0.2764      18.2079 (8)
                                                      :     ANGLE   4     -0.52648        0.3330      63.6559 (9)
                                                      :     RHOXAN  5     -0.68343        0.0782     145.4871 (8)
                                                      :     RHOSQ   6      0.26008        0.1337      12.0435 (7)
                                                      :     ANSQ    7     -0.56279        0.4338      85.3747 (7)
```

```
STEP NUMBER      2
VARIABLE ENTERED      4

MULTIPLE R              0.8901
STD. ERROR OF EST.      4.7272

ANALYSIS OF VARIANCE
                      DF    SUM OF SQUARES    MEAN SQUARE    F RATIO
      REGRESSION       2       14149.509        7074.754     316.593
      RESIDUAL       166        3709.520          22.347

               VARIABLES IN EQUATION                  :                  VARIABLES NOT IN EQUATION
  VARIABLE      COEFFICIENT  STD. ERROR  F TO REMOVE  :     VARIABLE    PARTIAL CORR.    TOLERANCE    F TO ENTER
                                                      :
  (CONSTANT       0.00000 )                           :
   RHO   3        0.01654     0.00082    411.5911 (9) :      BO     2      0.35469        0.0649      23.7456 (8)
   ANGLE 4       -0.04078     0.00511     63.6559 (9) :     RHOXAN  5     -0.60213        0.0649      93.8407 (8)
                                                      :     RHOSQ   6     -0.30606        0.0493      17.0531 (7)
                                                      :     ANSQ    7     -0.32004        0.0365      18.8291 (7)
```

```
STEP NUMBER      3
VARIABLE ENTERED      5

MULTIPLE R              0.9314
STD. ERROR OF EST.      3.7856

ANALYSIS OF VARIANCE
                      DF    SUM OF SQUARES    MEAN SQUARE    F RATIO
      REGRESSION       3       15494.422        5164.807     360.395
      RESIDUAL       165        2364.608          14.331

               VARIABLES IN EQUATION                  :                  VARIABLES NOT IN EQUATION
  VARIABLE      COEFFICIENT  STD. ERROR  F TO REMOVE  :     VARIABLE    PARTIAL CORR.    TOLERANCE    F TO ENTER
```

B

VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE		VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)							
RHO 3	0.02796	0.00135	430.5915 (9)		BO 2	-0.29746	0.0216	15.9217 (8)
ANGLE 4	-0.02284	0.00449	25.8447 (9)		RHOSQ 6	0.07783	0.0321	0.9995 (7)
RHOXAN 5	-0.00012	0.00001	93.8467 (8)		ANSQ 7	0.26592	0.0154	12.4791 (7)

STEP NUMBER 4
VARIABLE ENTERED 2

MULTIPLE R 0.9377
STD. ERROR OF EST. 3.6252

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	4	15703.672	3925.918	298.721
RESIDUAL	164	2155.358	13.142	

VARIABLES IN EQUATION					VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE		VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)							
BO 2	-7.59057	1.90230	15.9217 (8)		RHOSQ 6	-0.09354	0.0235	1.4388 (7)
RHO 3	0.03629	0.00245	218.6493 (9)		ANSQ 7	0.03664	0.0049	0.2216 (7)
ANGLE 4	0.03610	0.01538	5.5058 (9)					
RHOXAN 5	-0.00018	0.00002	82.7453 (8)					

STEP NUMBER 5
VARIABLE ENTERED 6

MULTIPLE R 0.9383
STD. ERROR OF EST. 3.6204

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	5	15722.530	3144.506	239.904
RESIDUAL	163	2136.499	13.107	

VARIABLES IN EQUATION					VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE		VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)							
BO 2	-8.97185	2.22152	16.3103 (8)		ANSQ 7	0.03701	0.0049	0.2222 (7)
RHO 3	0.04043	0.00423	91.1518 (9)					
ANGLE 4	0.03610	0.01536	5.5205 (9)					
RHOXAN 5	-0.00018	0.00002	82.9667 (8)					
RHOSQ 6	-0.00000	0.00000	1.4388 (7)					

STEP NUMBER 6
VARIABLE ENTERED 7

MULTIPLE R 0.9384
STD. ERROR OF EST. 3.6291

ANALYSIS OF VARIANCE

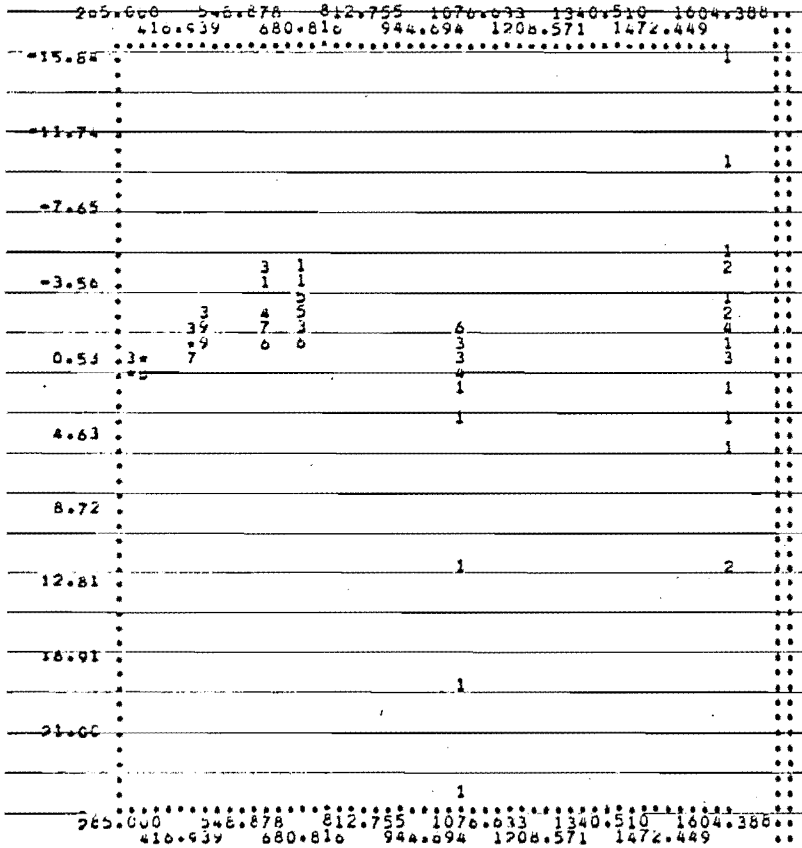
	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	6	15725.456	2620.909	199.003
RESIDUAL	162	2133.573	13.170	

VARIABLES IN EQUATION					VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE		VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER

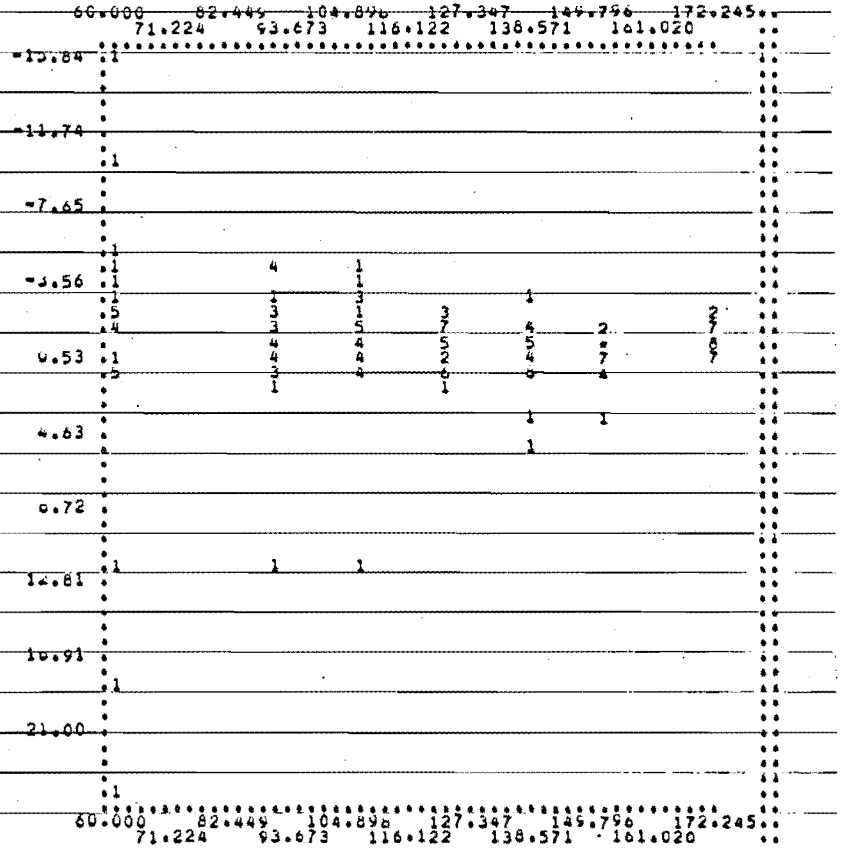
B

(CONSTANT		0.00000)		
BG	2	-7.64891	3.58784	4.5577 (8)
RHO	3	0.04043	0.00425	90.7169 (9)
ANGLE	4	0.01085	0.05575	0.0379 (9)
RHOXAN	5	-0.00018	0.00002	82.5708 (8)
RHOSW	6	-0.00000	0.00000	1.4319 (7)
ANSW	7	0.00011	0.00023	0.2222 (7)

PLOT OF RESIDUALS (Y-AXIS)
VS. VARIABLE 3 (X-AXIS)



PLOT OF RESIDUALS (Y-AXIS)
VS. VARIABLE 4 (X-AXIS)



SUMMARY TABLE B

STEP NUMBER	VARIABLE ENTERED	VARIABLE REMOVED	MULTIPLE R	MULTIPLE RSQ	INCREASE IN RSQ	F VALUE TO ENTER OR REMOVE	NUMBER OF INDEPENDENT VARIABLES INCLUDED
1	RHO 3		0.8442	0.7126	0.7126	414.1485	1
2	ANGLE 4		0.8901	0.7923	0.0797	63.6559	2
3	RHOXAN 5		0.9314	0.8676	0.0753	93.8467	3
4	BU 2		0.9377	0.8793	0.0117	15.9217	4
5	RHOSW 6		0.9383	0.8804	0.0011	1.4388	5
6	ANSW 7		0.9384	0.8805	0.0002	0.2222	6

SUB-PROBLEM 1
DEPENDENT VARIABLE 1
MAXIMUM NUMBER OF STEPS 10
F-LEVEL FOR INCLUSION 0.010000
F-LEVEL FOR DELETION 0.005000
TOLERANCE LEVEL 0.001000

C

STEP NUMBER 1
VARIABLE ENTERED 3

MULTIPLE R 0.8831
STD. ERROR OF EST. 4.0838

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	1	8446.299	8446.299	506.451
RESIDUAL	143	2384.871	16.677	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)						
RHO 3	0.00988	0.00044	506.4512 (9)	BO 2	-0.42464	0.2764	31.2373 (8)
				ANGLE 4	-0.56080	0.3068	72.2839 (9)
				RHOXAN 5	-0.73747	0.0420	169.3099 (8)
				RHOSQ 6	0.42347	0.1337	31.0292 (7)
				ANSQ 7	-0.64508	0.3793	101.2038 (7)

STEP NUMBER 2
VARIABLE ENTERED 4

MULTIPLE R 0.9242
STD. ERROR OF EST. 3.3361

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	2	9250.783	4625.391	415.598
RESIDUAL	142	1580.388	11.129	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)						
RHO 3	0.01446	0.00065	499.0049 (9)	BO 2	0.38139	0.0379	24.0010 (8)
ANGLE 4	-0.03250	0.00382	72.2839 (9)	RHOXAN 5	-0.71780	0.0379	149.8660 (8)
				RHOSQ 6	-0.15199	0.0366	3.3345 (7)
				ANSQ 7	-0.38430	0.0296	24.4324 (7)

STEP NUMBER 3
VARIABLE ENTERED 5

MULTIPLE R 0.9640
STD. ERROR OF EST. 2.3310

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	3	10065.064	3355.021	617.484
RESIDUAL	141	766.106	5.433	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER

C

VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)						
RHO 3	0.02836	0.00122	538.5197 (9)	BO 2	-0.56063	0.0116	64.1739 (8)
ANGLE 4	-0.02165	0.00281	59.2122 (9)	RHLSQ 6	0.37352	0.0261	22.7000 (7)
RHOXAN 5	-0.00012	0.00001	149.8660 (8)	ANSQ 7	0.49066	0.0099	46.3349 (7)

STEP NUMBER 4
VARIABLE ENTERED 2

MULTIPLE R 0.9754
STD. ERROR OF EST. 1.9371

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	4	10305.859	2576.465	686.650
RESIDUAL	140	525.311	3.752	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)						
BO 2	-11.99600	1.49747	64.1739 (8)	RHLSQ 6	0.19274	0.0235	5.3626 (7)
RHO 3	0.04153	0.00193	462.0854 (9)	ANSQ 7	-0.09250	0.0012	1.1996 (7)
ANGLE 4	0.06778	0.01141	35.3094 (9)				
RHOXAN 5	-0.00022	0.00001	219.9213 (8)				

STEP NUMBER 5
VARIABLE ENTERED 6

MULTIPLE R 0.9764
STD. ERROR OF EST. 1.9076

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	5	10325.373	2065.075	567.511
RESIDUAL	139	505.797	3.639	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)						
BO 2	-10.47636	1.61373	42.1621 (8)	ANSQ 7	-0.09427	0.0012	1.2374 (7)
RHO 3	0.03693	0.00274	182.7295 (9)				
ANGLE 4	0.06778	0.01123	36.4097 (9)				
RHOXAN 5	-0.00022	0.00001	226.7744 (8)				
RHLSQ 6	0.00000	0.00000	5.3626 (7)				

STEP NUMBER 6
VARIABLE ENTERED 7

MULTIPLE R 0.9766
STD. ERROR OF EST. 1.9059

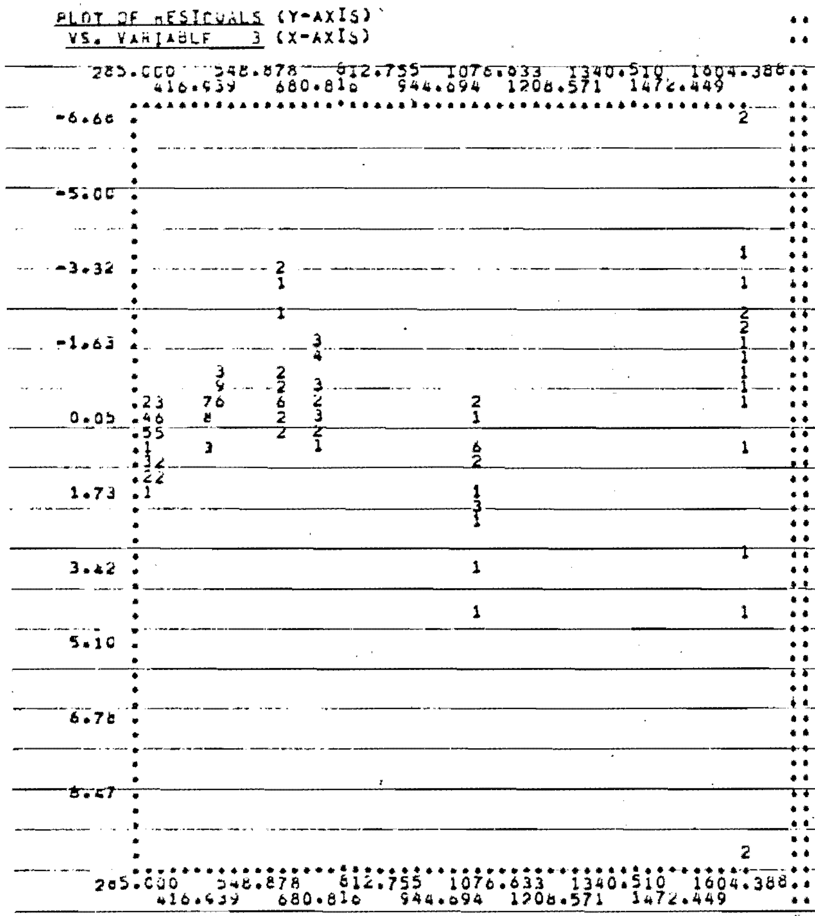
ANALYSIS OF VARIANCE

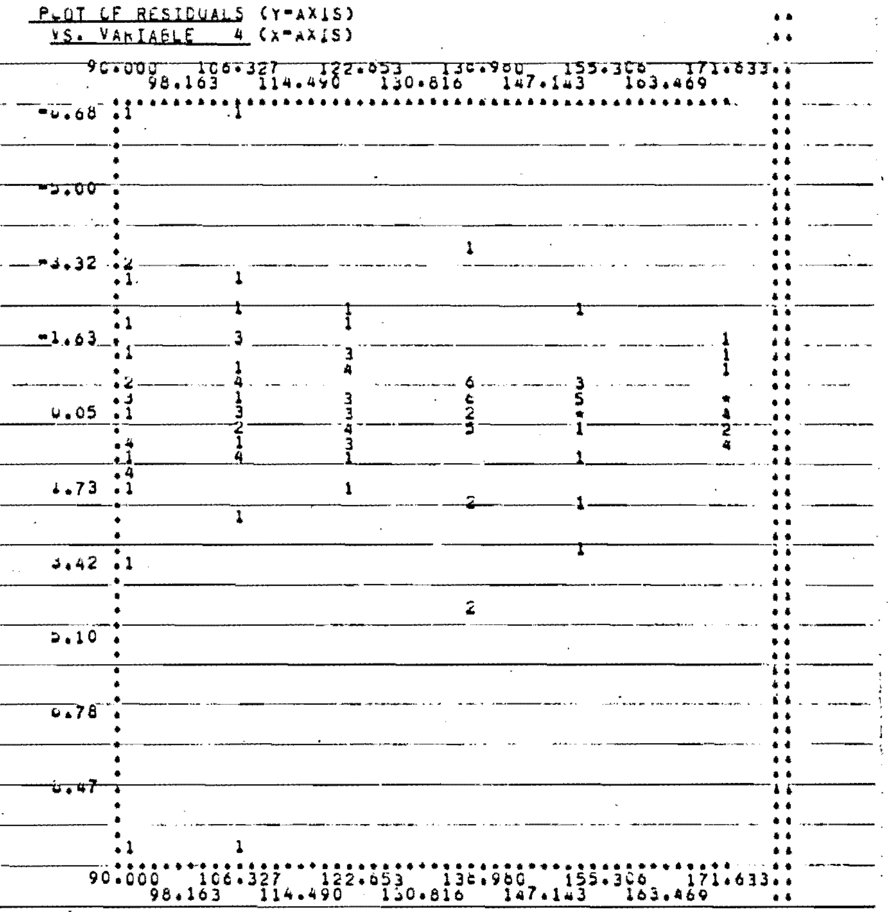
	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	6	10329.868	1721.645	473.939
RESIDUAL	138	501.302	3.633	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER

C

(CONSTANT		0.00000)			
BU	2	-14.07990	4.27281	12.1275	(8)
RPU	3	0.03698	0.00273	183.0415	(9)
ANGLE	4	0.13866	0.06470	4.5923	(9)
RPOXAN	5	-0.00022	0.00001	227.1617	(8)
RMDS.	6	0.00000	0.00000	5.3718	(7)
ANS.	7	-0.00027	0.00025	1.2374	(7)





SUMMARY TABLE

STEP NUMBER	VARIABLE ENTERED	VARIABLE REMOVED	MULTIPLE R	RSQ	INCREASE IN RSQ	F VALUE TO ENTER OR REMOVE	NUMBER OF INDEPENDENT VARIABLES INCLUDED
1	RHO 3		0.8831	0.7798	0.7798	506.4512	1
2	ANGLE 4		0.9242	0.8541	0.0743	72.2839	2
3	RHOXAN 5		0.9640	0.9293	0.0752	149.6666	3
4	BO 2		0.9754	0.9515	0.0222	64.1739	4
5	RHOSQ 6		0.9764	0.9533	0.0018	5.3626	5
6	ANSQ 7		0.9766	0.9537	0.0004	1.2374	6

D

SUB-PROBLEM 1
DEPENDENT VARIABLE 1
MAXIMUM NUMBER OF STEPS 10
F-LEVEL FOR INCLUSION 0.010000
F-LEVEL FOR DELETION 0.005000
TOLERANCE LEVEL 0.001000

STEP NUMBER 1
VARIABLE ENTERED 3

MULTIPLE R 0.9208
STD. ERROR OF EST. 1.3511

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	1	1271.296	1271.296	696.424
RESIDUAL	125	228.183	1.825	

VARIABLES IN EQUATION					VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	:	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)			:				
RHO 3	0.00678	0.00026	696.4242 (9)	:	BO 2	-0.17796	0.0794	4.0567 (8)
				:	ANGLE 4	-0.72141	0.1514	134.5700 (9)
				:	RHOXAN 5	-0.88622	0.0782	453.7996 (8)
				:	RHOSQ 6	0.20734	0.0537	5.5704 (7)
				:	ANSQ 7	-0.80080	0.2757	221.6801 (7)

STEP NUMBER 2
VARIABLE ENTERED 4

MULTIPLE R 0.9628
STD. ERROR OF EST. 0.9394

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	2	1390.051	695.026	787.583
RESIDUAL	124	109.428	0.882	

VARIABLES IN EQUATION					VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	:	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)			:				
RHO 3	0.01169	0.00046	647.9847 (9)	:	BO 2	0.65035	0.0410	90.1565 (8)
ANGLE 4	-0.02018	0.00174	134.5700 (9)	:	RHOXAN 5	-0.77517	0.0410	185.1871 (8)
				:	RHOSQ 6	-0.55036	0.0291	53.4429 (7)
				:	ANSQ 7	-0.54333	0.0249	51.5202 (7)

STEP NUMBER 3
VARIABLE ENTERED 5

MULTIPLE R 0.9853
STD. ERROR OF EST. 0.5959

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	3	1455.806	485.269	1366.490
RESIDUAL	123	43.673	0.355	

VARIABLES IN EQUATION					VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	:	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER

D

VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)						
RHO 3	0.01552	0.00041	1467.1257 (9)	BO 2	-0.25921	0.0062	8.7878 (8)
ANGLE 4	-0.00588	0.00152	14.9162 (9)	RHOSQ 6	0.41622	0.0068	25.5642 (7)
RHOXAN 5	-0.00006	0.00000	185.1671 (8)	ANSQ 7	0.27340	0.0079	9.8563 (7)

STEP NUMBER 4
VARIABLE ENTERED 2

MULTIPLE R 0.9863
STD. ERROR OF EST. 0.5779

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	4	1458.740	364.685	1092.114
RESIDUAL	122	40.739	0.334	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)						
BO 2	-1.93633	0.65319	8.7878 (8)	RHOSQ 6	0.34960	0.0029	16.8472 (7)
RHO 3	0.01949	0.00139	195.3213 (9)	ANSQ 7	0.14673	0.0049	2.7370 (7)
ANGLE 4	0.00915	0.00528	3.0013 (9)				
RHOXAN 5	-0.00009	0.00001	67.0963 (8)				

STEP NUMBER 5
VARIABLE ENTERED 6

MULTIPLE R 0.9880
STD. ERROR OF EST. 0.5436

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	5	1463.719	292.744	990.549
RESIDUAL	121	35.760	0.296	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)						
BO 2	1.02818	0.94829	1.1756 (8)	ANSQ 7	0.15674	0.0049	3.1021 (7)
RHO 3	0.00572	0.00360	2.5181 (9)				
ANGLE 4	0.00915	0.00497	3.3912 (9)				
RHOXAN 5	-0.00009	0.00001	75.8118 (8)				
RHOSQ 6	0.00001	0.00000	16.8472 (7)				

STEP NUMBER 6
VARIABLE ENTERED 7

MULTIPLE R 0.9883
STD. ERROR OF EST. 0.5390

ANALYSIS OF VARIANCE

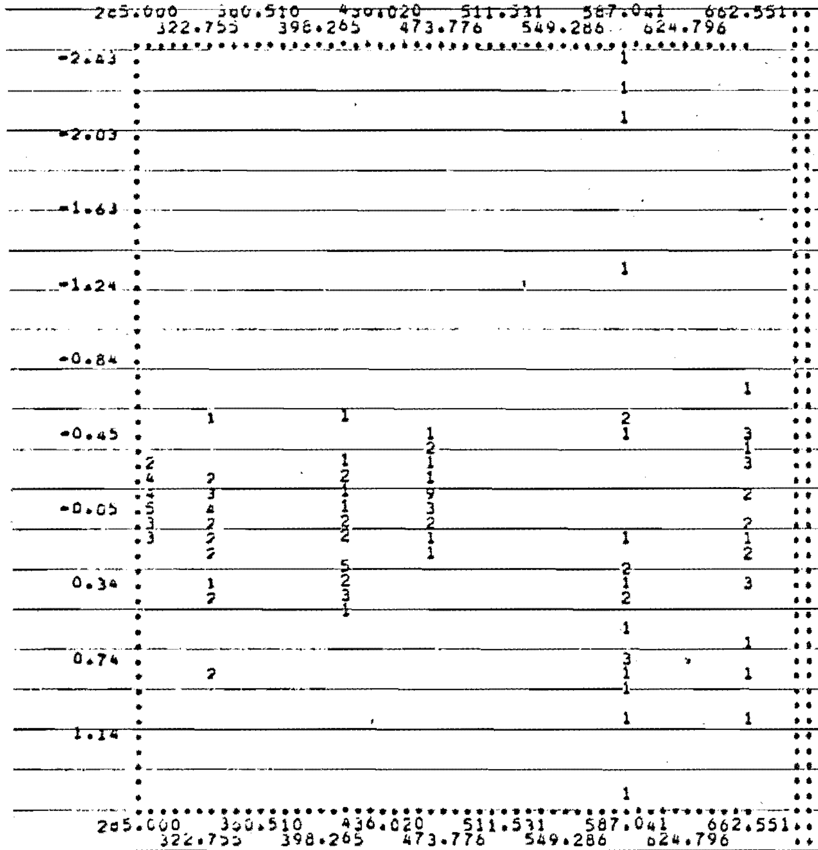
	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	6	1464.620	244.103	840.315
RESIDUAL	120	34.859	0.290	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER

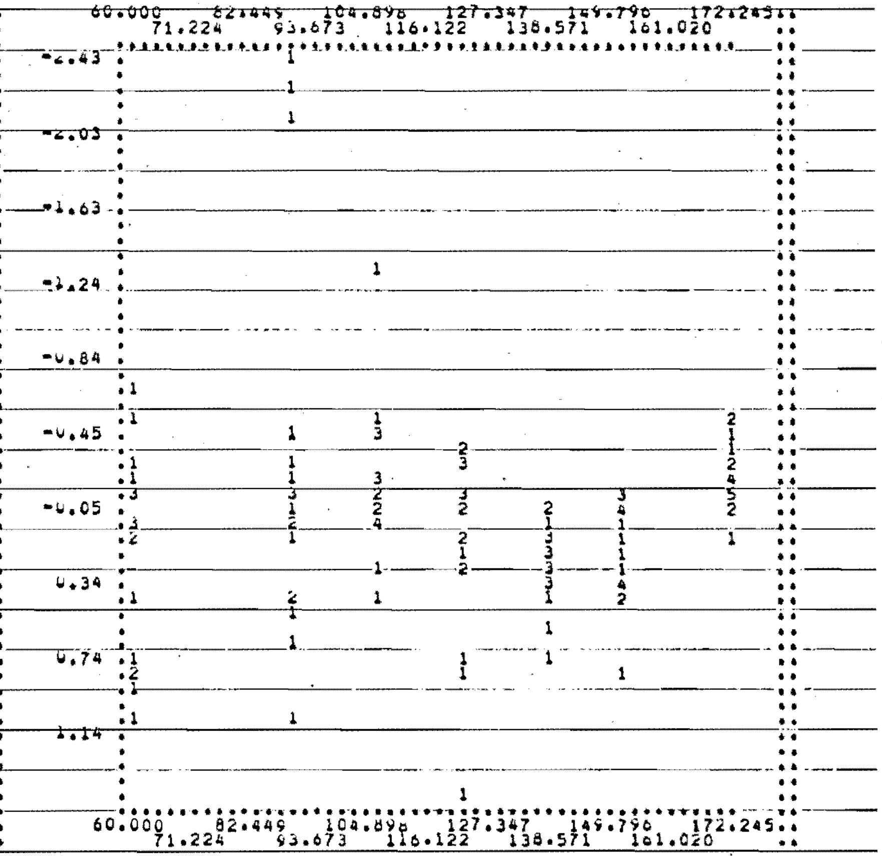
D

(CONSTANT		0.00000)		
BO	2	1.07594	1.05621	3.1546 (8)
RHO	3	0.00572	0.00357	2.5619 (9)
ANGLE	4	-0.00703	0.01043	0.4548 (9)
RHOXAN	5	-0.00009	0.00001	17.1289 (8)
RHOSW	6	0.00001	0.00000	17.1399 (7)
ANSW	7	0.00007	0.00004	3.1021 (7)

PLOT OF RESIDUALS (Y-AXIS)
VS. VARIABLE 3 (X-AXIS)



PLOT OF RESIDUALS (Y-AXIS)
VS. VARIABLE 4 (X-AXIS)



SUMMARY TABLE **D**

STEP NUMBER	VARIABLE ENTERED	REMOVED	MULTIPLE R	RSQ	INCREASE IN RSQ	F VALUE TO ENTER OR REMOVE	NUMBER OF INDEPENDENT VARIABLES INCLUDED
1	RHO 3		0.9208	0.8478	0.8478	696.4242	1
2	ANGLE 4		0.9628	0.9270	0.0792	134.5700	2
3	RHOXAN 5		0.9853	0.9709	0.0439	185.1871	3
4	BU 2		0.9863	0.9728	0.0020	8.7878	4
5	RHOSW 6		0.9880	0.9762	0.0033	16.6472	5
6	XNSW 7		0.9883	0.9768	0.0006	3.1021	6

E

SUB-PROBLEM 1
DEPENDENT VARIABLE 1
MAXIMUM NUMBER OF STEPS 10
F-LEVEL FOR INCLUSION 0.010000
F-LEVEL FOR DELETION 0.005000
TOLERANCE LEVEL 0.001000

STEP NUMBER 1
VARIABLE ENTERED 3

MULTIPLE R 0.8213
STD. ERROR OF EST. 22.2482

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	1	491225.973	491225.973	992.413
RESIDUAL	479	237096.165	494.982	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)						
RHO 3	0.05328	0.00169	992.4127 (9)	BO 2	-0.33867	0.1329	61.9273 (8)
				ANGLE 4	-0.69575	0.1944	448.4775 (9)
				RHOXAN 5	-0.87644	0.0743	1029.9344 (8)
				RHOSQ 6	0.37139	0.1186	76.4775 (7)
				ANSQ 7	-0.74641	0.3033	601.3178 (7)

STEP NUMBER 2
VARIABLE ENTERED 4

MULTIPLE R 0.9122
STD. ERROR OF EST. 15.9972

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	2	605996.486	302998.243	1183.997
RESIDUAL	478	122325.652	255.911	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)						
RHO 3	0.10572	0.00276	1468.7087 (9)	BO 2	0.45391	0.0521	123.7825 (8)
ANGLE 4	-0.27241	0.01286	448.4775 (9)	RHOXAN 5	-0.72435	0.0495	526.5280 (8)
				RHOSQ 6	-0.16674	0.0644	17.2341 (7)
				ANSQ 7	-0.36015	0.0258	83.5912 (7)

STEP NUMBER 3
VARIABLE ENTERED 5

MULTIPLE R 0.9593
STD. ERROR OF EST. 11.0406

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	3	670177.934	223392.645	1832.655
RESIDUAL	477	58144.204	121.896	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER

E

VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)						
RPC 3	0.10125	0.00306	2742.1097 (9)	BO 2	-0.55033	0.0118	213.3536 (8)
ANGLE 4	-0.12843	0.01087	139.5693 (9)	RHOSQ 6	0.53607	0.0374	193.9732 (7)
RHOXAN 5	-0.00067	0.00003	526.5280 (8)	ANSQ 7	0.55108	0.0061	208.2536 (7)

STEP NUMBER 4
VARIABLE ENTERED 2

MULTIPLE R 0.9720
STD. ERROR OF EST. 9.1640

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	4	688173.463	172043.366	2039.735
RESIDUAL	476	40148.675	84.346	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)						
BO 2	-56.35612	3.85825	213.3536 (8)	RHOSQ 6	0.43029	0.0322	107.9277 (7)
RPC 3	0.24850	0.00650	1461.6732 (9)	ANSQ 7	0.30463	0.0048	48.6596 (7)
ANGLE 4	0.29421	0.03032	94.1663 (9)				
RHOXAN 5	-0.00133	0.00005	675.4747 (8)				

STEP NUMBER 5
VARIABLE ENTERED 6

MULTIPLE R 0.9773
STD. ERROR OF EST. 8.2990

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	5	695606.695	139121.379	2019.935
RESIDUAL	475	32715.243	68.874	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)						
BO 2	-41.92485	3.75302	124.7903 (8)	ANSQ 7	0.29590	0.0047	45.4854 (7)
RPC 3	0.19191	0.00601	573.8773 (9)				
ANGLE 4	0.32069	0.02751	135.8684 (9)				
RHOXAN 5	-0.00137	0.00005	873.0505 (8)				
RHOSQ 6	0.00005	0.00000	107.9277 (7)				

STEP NUMBER 6
VARIABLE ENTERED 7

MULTIPLE R 0.9793
STD. ERROR OF EST. 7.9356

ANALYSIS OF VARIANCE

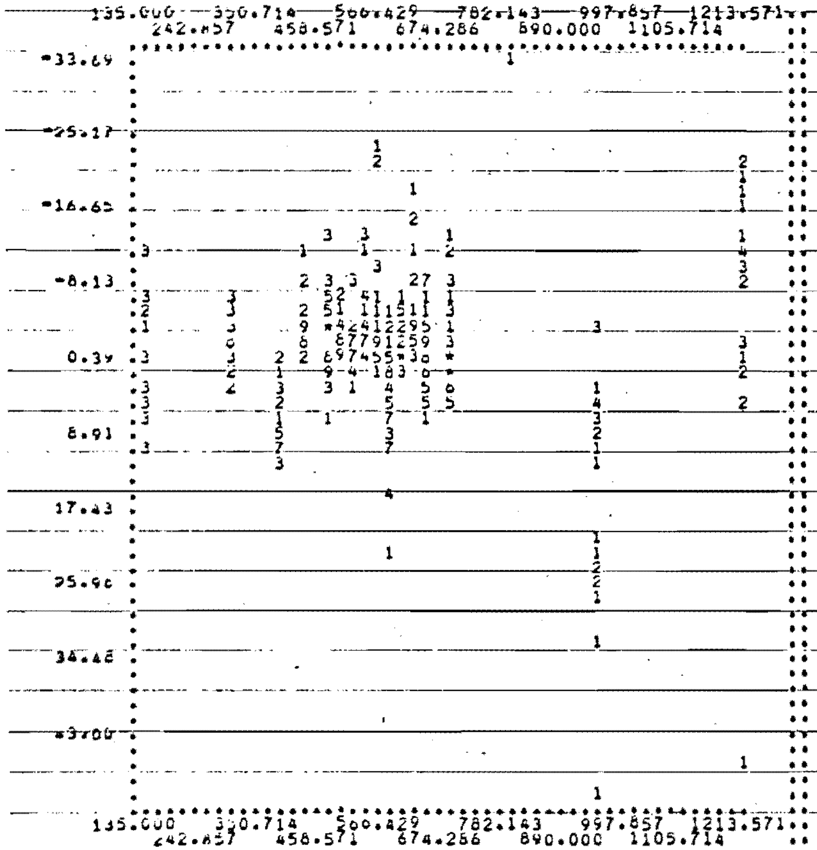
	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	6	698471.395	116411.899	1848.505
RESIDUAL	474	29850.743	62.976	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER

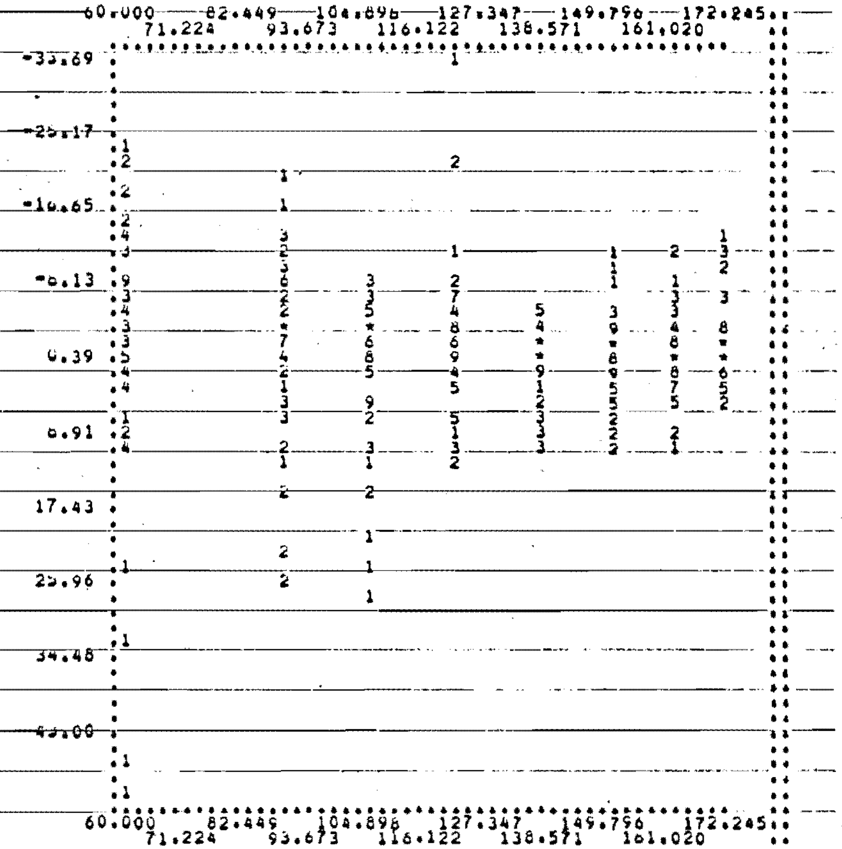
E

(CONSTANT	0.00000)			
BV 2	-23.70649	4.48465	28.1322	(8)
RHO 3	0.20250	0.00782	670.6309	(9)
ANGLE 4	-0.09357	0.06682	1.9610	(9)
RHOXAN 5	-0.00142	0.00004	990.3612	(8)
RHOSW 6	0.00004	0.00000	104.2611	(7)
ANSW 7	0.00192	0.00028	45.4854	(7)

PLOT OF RESIDUALS (Y-AXIS)
VS. VARIABLE 3 (X-AXIS)



PLOT OF RESIDUALS (Y-AXIS)
VS. VARIABLE 4 (X-AXIS)



SUMMARY TABLE E

STEP NUMBER	VARIABLE ENTERED	VARIABLE REMOVED	MULTIPLE R	MULTIPLE RSQ	INCREASE IN RSQ	F VALUE TO ENTER OR REMOVE	NUMBER OF INDEPENDENT VARIABLES INCLUDED
1	RHO 3		0.8213	0.6745	0.6745	992.4127	1
2	ANGLE 4		0.9122	0.8320	0.1576	448.4775	2
3	RHOXAN 5		0.9593	0.9202	0.0881	526.5200	3
4	SU 2		0.9720	0.9449	0.0247	213.3538	4
5	RHOSW 6		0.9773	0.9551	0.0102	107.9277	5
6	ANSW 7		0.9793	0.9590	0.0039	45.4854	6

F

SUB-PROBLEM 1
DEPENDENT VARIABLE 1
MAXIMUM NUMBER OF STEPS 10
F-LEVEL FOR INCLUSION 0.010000
F-LEVEL FOR DELETION 0.005000
TOLERANCE LEVEL 0.001000

STEP NUMBER 1
VARIABLE ENTERED 3

MULTIPLE R 0.8263
STD. ERROR OF EST. 19.3801

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	1	348478.148	348478.148	927.818
RESIDUAL	431	161878.784	375.589	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)						
RHO 3	0.04912	0.00161	927.8182 (9)	BO 2	-0.33927	0.1344	55.9326 (8)
				ANGLE 4	-0.70188	0.1952	417.5236 (9)
				RHOXAN 5	-0.83486	0.0743	989.0915 (8)
				RHOSQ 6	0.39062	0.1341	77.4260 (7)
				ANSQ 7	-0.75343	0.3040	564.5638 (7)

STEP NUMBER 2
VARIABLE ENTERED 4

MULTIPLE R 0.9160
STD. ERROR OF EST. 13.8204

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	2	428226.035	214113.018	1120.998
RESIDUAL	430	82130.897	191.002	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)						
RHO 3	0.09684	0.00260	1383.9963 (9)	BO 2	0.46623	0.0525	120.4653 (8)
ANGLE 4	-0.23885	0.01169	417.5236 (9)	RHOXAN 5	-0.73965	0.0497	518.1875 (6)
				RHOSQ 6	-0.14620	0.0744	9.3097 (7)
				ANSQ 7	-0.39494	0.0259	79.2797 (7)

STEP NUMBER 3
VARIABLE ENTERED 5

MULTIPLE R 0.9629
STD. ERROR OF EST. 9.3118

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	3	473158.221	157719.407	1818.924
RESIDUAL	429	37198.711	86.710	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER

F

VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)						
RHO 3	0.14777	0.00284	2701.6764 (9)	BO 2	-0.55673	0.0122	192.2420 (8)
ANGLE 4	-0.11262	0.00963	136.6886 (9)	RHOSQ 6	0.61219	0.0449	256.5490 (7)
RHOXAN 5	-0.00061	0.00003	518.1675 (8)	ANSQ 7	0.57464	0.0082	211.0021 (7)

STEP NUMBER 4
VARIABLE ENTERED 2

MULTIPLE R 0.9745
STD. ERROR OF EST. 7.7443

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	4	484687.840	121171.960	2020.391
RESIDUAL	428	25669.092	59.975	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)						
BO 2	-46.91165	3.38343	192.2420 (8)	RHOSQ 6	0.53635	0.0394	172.4397 (7)
RHO 3	0.22311	0.00593	1417.5315 (9)	ANSQ 7	0.34363	0.0049	57.1700 (7)
ANGLE 4	0.23962	0.02664	80.9197 (9)				
RHOXAN 5	-0.00118	0.00005	641.1948 (8)				

STEP NUMBER 5
VARIABLE ENTERED 6

MULTIPLE R 0.9819
STD. ERROR OF EST. 6.5438

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	5	492072.018	98414.404	2298.231
RESIDUAL	427	18284.914	42.822	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	0.00000)						
BO 2	-32.66798	3.05189	116.1279 (8)	ANSQ 7	0.35010	0.0048	59.5104 (7)
RHO 3	0.10708	0.00658	644.9999 (9)				
ANGLE 4	0.26813	0.02261	140.5969 (9)				
RHOXAN 5	-0.00123	0.00004	961.9825 (8)				
RHOSQ 6	0.00005	0.00000	172.4397 (7)				

STEP NUMBER 6
VARIABLE ENTERED 7

MULTIPLE R 0.9842
STD. ERROR OF EST. 6.1369

ANALYSIS OF VARIANCE

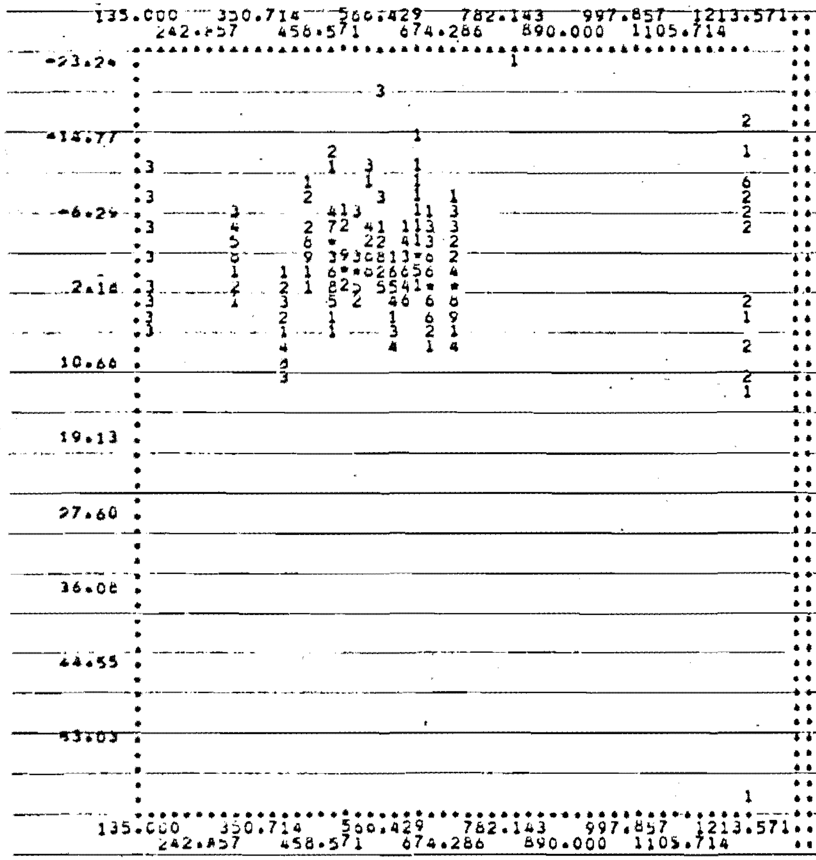
	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	6	494313.252	82385.542	2187.543
RESIDUAL	426	16043.680	37.661	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER

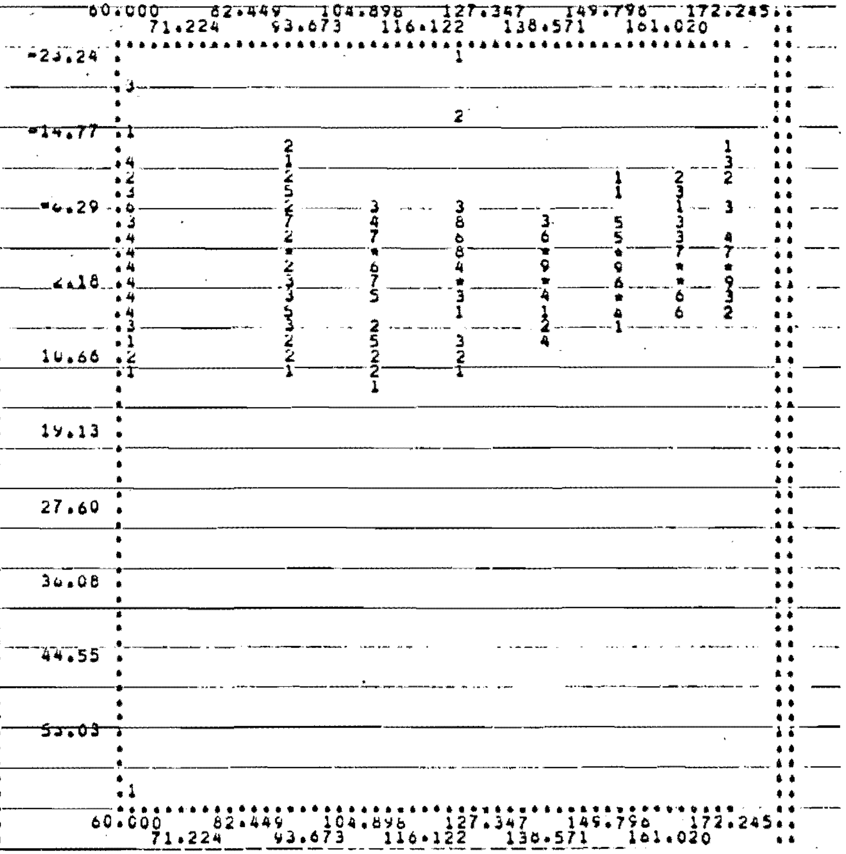
F

(CONSTANT		0.00000)			
ED	2	-16.44409	3.56866	21.2329	(8)
RFC	3	-0.17766	0.00632	790.1608	(9)
ANGLE	4	-0.11251	0.05371	4.3885	(9)
RHOXAR	5	-0.00128	0.00004	1151.0680	(8)
RHOSQ	6	0.00004	0.00000	175.0992	(7)
ANSQ	7	0.00177	0.00023	59.5104	(7)

PLOT OF RESIDUALS (Y-AXIS) VS. VARIABLE 3 (X-AXIS)



PLOT OF RESIDUALS (Y-AXIS) VS. VARIABLE 4 (X-AXIS)



SUMMARY TABLE F

STEP NUMBER	VARIABLE ENTERED	VARIABLE REMOVED	MULTIPLE R	MULTIPLE RSQ	INCREASE IN RSQ	F VALUE TO ENTER OR REMOVE	NUMBER OF INDEPENDENT VARIABLES INCLUDED
1	RHO 3		0.8263	0.6828	0.6828	927.8182	1
2	ANGLE 4		0.9160	0.8391	0.1563	417.5236	2
3	RHOXAN 5		0.9629	0.9271	0.0880	518.1875	3
4	BU 2		0.9745	0.9497	0.0226	192.2420	4
5	RHOSW 6		0.9819	0.9642	0.0145	172.4397	5
6	ANSW 7		0.9842	0.9686	0.0044	59.5104	6

Table 27A - Summary of Wedge (Nominal) Hardness results. Air dry.

Species	60°	90^{0}	105°	120°
Balsa	4.91 (1.2)	2.03 (3.1)	1.45 (2.5)	1.43 (3.6)
Strobus pine	16.99 (5.0)	6.88 (7.0)	6.33 (8.1)	4.00 (0.0)
Douglas fir	37.88 (1.9)	29.68 (3.1)	25.14 (3.4)	21.94 (9.8)
Pukatea	24.47 (6.3)	18.36 (3.9)	13.61 (3.2)	10.97 (0.6)
Kahikatea	33.58 (4.3)	23.10 (0.6)	24.27 (11.7)	19.29 (4.1)
Kauri	41.53 (2.0)	12.28 (3.6)	12.59 (1.2)	9.73 (2.2)
Tawa	39.15 (0.1)	29.92 (3.2)	24.97 (2.1)	19.10 (2.1)
Scots pine	42.51 (1.6)	26.02 (1.3)	21.02 (1.3)	12.24 (6.8)
Mangeao	36.47 (0.0)	25.51 (11.7)	21.09 (4.5)	18.32 (2.1)
Rewarewa	57.36 (5.0)	42.40 (0.0)	29.08 (2.6)	21.10 (4.7)
Hard beech	52.87 (2.9)	42.77 (3.3)	35.68 (5.9)	30.98 (0.4)
Douglas fir	61.96 (4.5)	57.29 (6.9)	45.62 (6.3)	31.48 (12.6)
Hinau	31.06 (2.2)	26.73 (1.9)	24.32 (4.4)	23.46 (1.9)
European beech	49.72 (4.8)	36.64 (5.5)	33.48 (0.0)	25.00 (1.3)
Pohutukawa	62.64 (1.9)	46.26 (0.0)	37.36 (3.3)	29.82 (2.6)
Northern rata	60.58 (0.5)	39.38 (0.1)	37.27 (5.0)	30.20 (1.6)
Mapou	64.69 (1.9)	48.78 (4.8)	43.49 (0.0)	26.77 (3.6)
Puriri	77.18 (0.0)	57.35 (3.2)	49.93 (0.0)	36.30 (2.3)
Southern rata	142.23 (4.2)	116.86 (1.5)	100.60 (3.3)	70.69 (3.5)
Southern rata	161.25 (8.2)	122.64 (8.3)	118.00 (1.6)	75.44 (8.5)

Appendix G

Table 27A - Summary of Wedge (Nominal) Hardness results. Air dry. (continued)

Species	136°	150°	160°	170°
Balsa	1.16 (4.2)	0.78 (8.5)	0.57 (9.7)	0.34 (16.0)
Strobus pine	3.12 (3.7)	2.21 (8.6)	1.96 (0.1)	1.46 (0.0)
Douglas fir	17.69 (3.4)	13.74 (4.4)	10.61 (3.1)	8.30 (7.8)
Pukatea	9.16 (1.0)	7.07 (1.2)	7.87 (14.2)	4.58 (8.1)
Kahikatea	13.68 (5.6)	10.65 (0.6)	8.59 (8.5)	6.84 (2.9)
Kauri	7.42 (0.4)	5.50 (0.6)	4.91 (2.0)	3.72 (5.8)
Tawa	16.08 (0.9)	13.78 (2.3)	9.67 (3.3)	6.87 (14.3)
Scots pine	13.70 (1.7)	10.72 (0.0)	6.67 (1.5)	4.62 (5.3)
Mangeao	13.61 (7.4)	10.92 (5.6)	8.99 (6.4)	6.37 (12.8)
Rewarewa	21.05 (3.4)	14.19 (5.0)	10.04 (12.6)	8.29 (9.6)
Hard beech	19.02 (2.8)	16.19 (2.4)	11.13 (3.9)	7.42 (3.8)
Douglas fir	26.74 (6.0)	23.24 (4.0)	20.12 (2.2)	12.20 (11.8)
Hinau	15.18 (0.9)	15.18 (0.7)	10.77 (2.9)	6.39 (6.0)
European beech	19.90 (1.7)	12.44 (1.0)	10.04 (9.6)	9.03 (3.0)
Pohutukawa	19.46 (1.5)	15.24 (2.2)	14.42 (0.0)	9.98 (4.4)
Northern rata	28.59 (1.4)	19.96 (6.4)	17.15 (3.2)	12.71 (6.5)
Mapou	23.20 (13.1)	21.54 (5.3)	15.21 (3.9)	9.59 (15.0)
Puriri	23.8 (9.5)	21.17 (2.2)	18.33 (0.0)	12.39 (9.4)
Southern rata	53.28 (5.7)	41.11 (2.9)	30.91 (1.0)	14.80 (4.3)
Southern rata	72.92 (1.8)	45.36 (4.9)	32.81 (6.2)	20.23 (10.9)

Appendix G

Table 27B - Summary of Wedge (Nominal) Hardness results. Green.

Species	90°	105°	120°	136°	150°	160°	170°
Balsa	3.99 (7.4)	3.48 (1.2)	2.94 (4.6)	2.25 (0.0)	1.68 (0.0)	1.36 (2.6)	0.71 (3.0)
Strobus pine	6.48 (3.2)	5.32 (0.0)	4.24 (11.0)	3.23 (0.1)	2.54 (4.4)	1.86 (3.4)	1.11 (8.2)
Douglas fir	15.18 (1.4)	12.69 (4.8)	11.03 (2.9)	7.99 (0.1)	5.86 (2.3)	4.82 (1.0)	3.79 (0.0)
Pukatea	9.04 (3.9)	6.83 (12.0)	4.92 (17.0)	4.55 (1.4)	3.34 (0.0)	2.41 (2.6)	1.54 (18.0)
Kahikatea	12.95 (12.8)	10.62 (6.0)	7.68 (2.8)	5.64 (0.0)	4.48 (1.2)	3.64 (0.0)	2.74 (13.7)
Kauri	12.11 (0.0)	8.92 (3.3)	6.55 (6.3)	5.61 (2.0)	4.45 (2.2)	3.74 (2.1)	2.49 (8.7)
Tawa	18.84 (9.9)	14.76 (4.5)	10.01 (4.2)	8.17 (1.5)	6.59 (12.0)	4.84 (1.5)	3.41 (6.0)
Scots pine	15.26 (1.0)	10.76 (18.7)	8.85 (15.0)	7.15 (1.2)	3.97 (1.0)	3.20 (5.0)	2.80 (22.2)
Mangeao	13.01 (5.2)	9.29 (1.6)	8.80 (2.0)	7.48 (7.4)	5.64 (0.0)	4.76 (3.6)	3.18 (4.9)
Rewarewa	13.43 (7.6)	12.14 (0.1)	9.68 (1.0)	5.87 (4.3)	4.49 (0.1)	4.59 (9.4)	2.68 (10.6)
Hard beech	40.38 (5.6)	31.79 (0.0)	24.72 (9.4)	17.81 (9.4)	12.19 (1.0)	8.89 (1.6)	6.38 (1.4)
Douglas fir	31.93 (1.2)	23.51 (2.1)	18.86 (5.7)	14.03 (8.5)	10.94 (5.0)	8.82 (2.5)	5.76 (6.1)
Hinau	28.84 (7.5)	21.31 (1.2)	16.21 (4.6)	12.52 (8.5)	10.66 (4.3)	9.65 (4.5)	6.07 (13.7)
European beech	20.57 (5.2)	16.61 (0.0)	12.62 (1.8)	9.64 (0.0)	7.29 (0.0)	6.66 (26.0)	3.63 (6.0)
Pohutukawa	26.00 (5.3)	20.22 (0.1)	17.16 (6.2)	12.18 (1.9)	7.98 (4.2)	6.72 (15.6)	5.44 (4.9)
Northern rata	27.71 (0.0)	22.41 (5.4)	17.29 (0.0)	14.52 (5.0)	11.22 (1.5)	9.07 (0.0)	6.40 (0.1)
Mapou	25.97 (1.8)	21.12 (9.8)	15.11 (12.9)	14.18 (2.5)	11.96 (2.5)	9.09 (11.0)	7.14 (0.0)
Puriri	40.48 (0.0)	33.74 (0.0)	25.97 (2.9)	19.35 (0.0)	14.53 (3.9)	9.79 (0.0)	5.77 (0.0)
Southern rata	-	-	-	-	-	-	-
Southern rata	25.89 (3.4)	21.29 (5.6)	16.13 (1.8)	13.31 (0.0)	9.89 (3.0)	8.51 (0.0)	5.69 (3.9)

Appendix G Table 28

AIR DRY

Species	Common Name	Density (kg/m^3) unadjusted	Density (kg/m^3) adjusted	Bending Strength (N/mm^2) MOR	Bending Strength (N/mm^2) MOE	Janka Hardness (side) (N/mm^2)	Compressive strength parallel to grain (N/mm^2)	Compressive strength perpendicular to grain (N/mm^2)	Strength in shear parallel to grain (N/mm^2)	Cleavage strength parallel to grain (N/mm)	Wedge Hardness 136° (N/mm^2)
Ochroma lagopus	Balsa	141	135	2.46 (32)	3.11 (28.3)	2.1 (0.0)	24.62 (2.8)	0.84 (8.9)	1.69 (7.8)	34.38 (15.4)	1.16 (4.2)
Pinus strobus	Strobus pine	303	276	6.18 (16.5)	4.67 (1.5)	29.4 (7.7)	36.14 (10.5)	3.14 (8.3)	8.44 (14.1)	59.6 (11.8)	3.12 (3.7)
Pseudotsuga menziesii	Douglas fir	418	379	7.33 (27.2)	7.79 (33.4)	17.4 (5.7)	36.75 (13.1)	8.14 (6.8)	11.38 (9.5)	81.4 (13.8)	17.69 (3.4)
Laurelia novae-zelandiae	Pukatea	441	416	6.79 (1.00)	7.47 (9.50)	26.3 (13.4)	36.00 (9.7)	6.42 (9.2)	9.77 (16.2)	90.3 (28.1)	9.16 (1.0)
Dacrycarpus dacrydioides	Kahikatea	478	451	8.36 (2.6)	8.99 (5.2)	28.7 (12.2)	38.95 (4.6)	8.54 (6.7)	13.26	78.6 (10.8)	13.68 (5.6)
Agathis autralis	Kauri	491	448	8.13 (7.7)	8.99 (18.6)	38.0 (1.7)	45.90 (8.4)	10.81 (2.1)	12.52 (31.6)	85.4 (12.2)	7.42 (0.4)
Beilschmedia tawa	Tawa	524	503	10.19 (0.6)	10.59 (1.7)	37.3 (1.0)	48.08 (3.5)	11.11 (4.6)	14.50 (2.4)	179.4 (8.2)	16.08 (0.9)
Pinus sylvestris	Scots pine	526	477	9.16 (4.0)	9.27 (1.3)	86.1 (1.5)	44.09 (5.1)	5.21 (7.0)	10.94 (27.0)	129.7 (5.6)	13.70 (1.7)
Litsea calicaris	Mangeao	553	518	5.24 (4.0)	5.17 (4.6)	43.7 (1.0)	33.08 (8.1)	11.42 (7.2)	12.34 (12.2)	132.5 (15.4)	13.61 (7.4)
Knightia excelsa	Rewarewa	598	579	10.46 (6.3)	9.85 (26.3)	47.1 (12.7)	49.33 (16.8)	14.40 (6.9)	11.83 (6.9)	139.7 (21.4)	21.05 (3.4)
Northofagus truncata	Hard beech	608	556	16.28 (3.9)	14.59 (12.9)	50.8 (9.7)	53.00 (8.6)	9.67 (4.2)	15.83 (6.4)	141.4 (8.0)	19.02 (2.8)
Pseudotsuga menziesii	Douglas fir	628	562	12.32 (24.7)	13.95 (15.62)	47.0 (9.6)	65.50 (13.3)	15.33 (11.7)	14.95 (12.2)	112.2 (17.8)	26.74 (6.0)
Elaeocarpus dentatus	Hinau	633	541	6.80 (3.5)	7.85 (14.14)	39.5 (3.1)	43.50 (6.7)	7.25 (12.4)	13.89 (8.3)	136.1 (11.7)	15.18 (0.9)
Fagus sylvatica	European beech	636	614	12.15 (3.4)	11.07 (2.1)	61.0 (2.4)	56.17 (8.6)	14.93 (2.2)	17.90 (13.2)	222.1 (13.5)	19.90 (1.7)
Metrosideros excelsa	Pohutukawa	674	630	9.77 (17.7)	8.73 (2.1)	80.6 (2.7)	45.55 (2.1)	23.23 (3.4)	17.4 (5.5)	259.3 (22.4)	19.47 (1.5)
Metrosideros robusta	Northern rata	697	630	7.18 (7.2)	6.73 (4.5)	66.5 (7.4)	52.53 (5.7)	14.13 (5.5)	17.16 (9.1)	277.0 (54.0)	28.59 (1.4)
Myrsine australis	Mapou	746	676	12.16 (0.7)	10.10 (8.2)	31.8 (1.1)	41.55 (1.3)	58.82 (7.6)	22.73 (11.1)	245.8 (2.6)	23.20 (13.1)
Vitex lucens	Puriri	813	679	13.83 (17.2)	13.05 (6.8)	86.5 (8.9)	62.98 (5.8)	23.17 (4.7)	21.22 (12.5)	283.8 (11.5)	23.8 (9.5)
Metrosideros umbellata	Southern rata	1000	936	20.55 (6.0)	20.26 (14.1)	178.2 (6.6)	95.22 (6.9)	51.09 (5.3)	28.21	396.7 (14.7)	53.28 (5.7)
Metrosideros umbellata	Southern rata	1274	1192	20.44 (5.6)	21.27 (17.63)	161.0 (4.4)	104.58 (4.2)	41.91 (4.1)	29.03 (7.2)	465.8 (11.2)	72.92 (1.8)

Appendix G Table 29 Green	Bending Strength (N/mm²) MOR	(N/mm²) MOE	Janka Hardness (side) (N/mm²)	Strength in shear parallel to grain (N/mm²)	Cleavage strength parallel to grain (N/mm)	Wedge Hardness 136° (N/mm²)
Balsa	1.03 (14.2)	1.24 (12.4)	1.47 (6.4)	0.25 (38.0)	26.30 (34.3)	2.94 (4.5)
Strobus pine	3.88 (8.9)	3.12 (6.2)	11.76 (8.8)	0.86 (39.3)	56.60 (33.6)	3.23 (0.8)
Douglas fir	4.07 (13.2)	5.81 (9.7)	11.31 (4.2)	5.95 (4.7)	65.90 (5.7)	7.99 (1.0)
Pukatea	3.42 (11.8)	4.11 (14.4)	20.30 (7.3)	5.84 (8.6)	85.30 (14.7)	4.54 (1.4)
Kahikatea	4.69 (8.0)	6.76 (14.8)	17.85 (8.1)	6.32 (1.9)	70.80 (18.8)	5.63 (0.3)
Kauri	4.01 (3.9)	7.27 (34.5)	18.69 (2.3)	3.05 (2.5)	65.90 (35.0)	5.61 (2.0)
Tawa	4.73 (3.6)	6.28 (4.8)	25.36 (6.1)	7.64 (9.8)	115.90 (6.6)	8.18 (1.5)
Scots pine	4.63 (0.03)	6.53 (8.9)	41.32 (2.1)	5.92 (5.7)	85.00 (13.7)	7.15 (1.2)
Mangeao	3.34 (14.2)	3.57 (6.5)	31.40 (5.2)	8.20 (32.7)	110.10 (17.1)	7.48 (7.2)
Rewarewa	4.52 (12.7)	5.52 (8.8)	32.98 (9.9)	4.73 (27.0)	113.70 (10.4)	5.87 (4.2)
Hard beech	6.83 (1.9)	10.39 (5.6)	44.70 (9.9)	7.90 (7.5)	178.10 (18.4)	17.81 (9.3)
Douglas fir	6.49 (17.7)	9.24 (32.7)	27.46 (4.8)	7.49 (20.3)	104.5 (30.6)	14.03 (8.4)
Hinau	5.34 (8.8)	5.66 (7.3)	35.80 (6.1)	8.80 (8.8)	135.30 (17.5)	12.52 (8.6)
European beech	5.88 (7.2)	6.66 (11.1)	48.07 (1.1)	8.69 (2.4)	161.25 (35.0)	9.64 (0.3)
Pohutukawa	7.28 (7.28)	8.92 (11.9)	57.47 (2.9)	8.37 (10.9)	216.80 (5.8)	12.18 (1.9)
Northern rata	4.71 (13.2)	5.35 (38.0)	53.86 (10.9)	9.35 (11.1)	203.90 (6.9)	14.52 (4.8)
Mapou	6.53 (4.6)	6.60 (2.6)	23.69 (10.4)	9.53 (11.9)	195.30 (30.3)	14.18 (2.5)
Puriri	8.51 (2.4)	8.92 (4.7)	66.29 (7.7)	11.41 (7.0)	194.20 (15.5)	19.35 (0.0)
Southern rata	-	-	-	-	-	-
Southern rata	14.86 (34.0)	20.90 (71.0)	77.28 (12.1)	9.75 (4.2)	276.50 (6.2)	13.31 (1.0)

Agathis australis	*kauri*
Beilschmedia tawa	*tawa*
Chamaecyparis obtusa	*hinoki cypress*
Chamaecyparis taiwanensis	*taiwanhinoki*
Podo *Dacrycarpus dacrydioides*	*kahikatea*
Elaeocarpus dentatus	*hinau*
Fagus crenata	buna
Fagus sylvatica	*European beech*
Knightia excelsa	*rewarewa*
Laurelia novae-zelandiae	*pukatea*
Litsea calicaris	*mangeao*
Metrosideros excelsa	*pohutukawa*
Metrosideros robusta	*northern rata*
Metrosideros umbellata	*southern rata*
Myrsine australis	*mapou*
Northofagus truncata	*hard beech*
Ochroma lagopus	*balsa*
Olea europeae	*olive*
Picea abies	*Norway spruce*
Pinus strobus	*strobus pine or Weymouth pine*
Pinus sylvestris	*Scots pine*
Pseudotsuga menziezii	*Douglas fir*
Quercus crispula	*Japanese oak*
Quercus robur	*English oak*
Vitex lucens	*puriri*

Species referred to in this work